PRICE TEN SHILLINGS AND SIXPENCE

THE JOURNAL OF
The Institution of Electrical Engineers

ORIGINALLY
The Society of Telegraph Engineers
FOUNDED 1871

INCORPORATED BY ROYAL CHARTER 1921

EDITED BY P. F. ROWELL, SECRETARY
SAVOY PLACE, VICTORIA EMBANKMENT, LONDON, W.C.2

Telegrams: "VOLTAMPERE, PHONE, LONDON." Telephone: TEMPLE BAR 7676.

Vol. 83 OCTOBER, 1938 No. 502

CONTENTS.

(The Institution is not, as a body, responsible for the opinions expressed by individual authors or speakers.)

PAGE

Recent Progress in Power Rectifiers and their Applications ...... W. G. THOMPSON, Ph.D., B.Sc. 437

Plastics and Electrical Insulation.
L. HARTSHORN, D.Sc., N. J. L. MEGSON, M.Sc., and E. RUSHTON, B.Sc. 474

Current Rating and Impedance of Cables in Buildings and Ships (E.R.A. Report Ref. F/T115).
H. C. BOOTH, E. E. HUTCHINGS, B.Sc.(Eng.), and S. WHITEHEAD, M.A., Ph.D. 497

Current Rating of Cables for Transmission and Distribution (E.R.A. Report Ref. F/T117).
S. WHITEHEAD, M.A., Ph.D., and E. E. HUTCHINGS, B.Sc.(Eng.) 517

Rotational Hysteresis Loss in Electrical Sheet Steels ...... F. BRAILSFORD, Wh.Sc., B.Sc.(Eng.) 566

Discussion on "Modern Systems of Multi-Channel Telephony on Cables" 576

Institution Notes 579

Advertisements .... At end i–xviii

E. and F. N. SPON LIMITED, 57 HAYMARKET, LONDON, S.W.1.
CHEMICAL PUBLISHING COMPANY OF N.Y. INC., 148 LAFAYETTE STREET, NEW YORK.

The Institution of Electrical Engineers.

FOUNDED 1871

INCORPORATED BY ROYAL CHARTER 1921

PATRON: HIS MAJESTY KING GEORGE VI.

COUNCIL, 1938-1939.

President.

A. P. M. FLEMING, C.B.E., D.Eng., M.Sc.

Past-Presidents.

COLONEL R. E. CROMPTON, C.B., F.R.S.
SIR JAMES SWINBURNE, BART., F.R.S.
CHARLES P. SPARKS, C.B.E.
ROGER T. SMITH.
LL. B. ATKINSON.
J. S. HIGHFIELD.
F. GILL, O.B.E.
A. RUSSELL, M.A., D.Sc., LL.D., F.R.S.
W. B. WOODHOUSE.
W. H. ECCLES, D.Sc., F.R.S.
SIR ARCHIBALD PAGE.
LIEUT.-COL. K. EDGCUMBE, T.D.
COLONEL SIR THOMAS F. PURVES, O.B.E.
CLIFFORD C. PATERSON, O.B.E., D.Sc.
J. M. DONALDSON, M.C.
PROF. E. W. MARCHANT, D.Sc.
P. V. HUNTER, C.B.E.
PROF. W. M. THORNTON, O.B.E., D.Sc., D.Eng.
J. M. KENNEDY, O.B.E.
H. T. YOUNG.
SIR GEORGE LEE, O.B.E., M.C.

Vice-Presidents.

SIR NOEL ASHBRIDGE, B.Sc. (Eng.).
J. R. BEARD, M.Sc.
PROF. C. L. FORTESCUE, O.B.E., M.A.
JOHNSTONE WRIGHT.

Honorary Treasurer.

W. MCCLELLAND, C.B., O.B.E.

Ordinary Members of Council.

T. E. ALLIBONE, D.Sc., Ph.D.
COL. A. S. ANGWIN, D.S.O., M.C.
L. G. BRAZIER, Ph.D., B.Sc.
T. CARTER.
P. DUNSHEATH, O.B.E., M.A., D.Sc.
C. E. FAIRBURN, M.A.
F. FORREST.
PROF. R. O. KAPP, B.Sc.
E. M. LEE, B.Sc.
E. LEETE.
S. W. MELSOM.

Ordinary Members of Council—(*Continued*).

P. L. RIVIÈRE.
P. J. ROBINSON, M.Eng.
C. RODGERS, O.B.E., B.Sc., B.Eng.
C. D. TAITE.
C. R. WESTLAKE.
G. A. WHIPPLE, M.A.
A. P. YOUNG, O.B.E.

Chairmen and Past-Chairmen of Local Centres.

Argentine Centre:
C. G. BARKER.
*H. C. SIDDELEY.

China Centre:
S. FLEMONS.
*C. S. TAYLOR.

Irish Centre:
J. W. O'NEILL.
*LT.-COL. K. E. EDGEWORTH, D.S.O., M.C.

Mersey and North Wales (Liverpool) Centre:
E. L. MORLAND.
*G. K. PATON.

North-Eastern Centre:
F. A. ORCHARD.
*W. D. HORSLEY.

North Midland Centre:
J. W. ATKINSON.
*J. G. CRAVEN.

North-Western Centre:
W. FENNELL.
*J. W. THOMAS, LL.B., B.Sc.Tech.

Scottish Centre:
W. J. COOPER.
*MAJOR H. BELL, O.B.E., T.D.

South Midland Centre:
H. FAULKNER, B.Sc.
*H. HOOPER.

Western Centre:
H. S. ELLIS.
*H. G. WEAVER.

* Past-Chairman.

Chairmen of Sections.

CAPTAIN B. S. COHEN, O.B.E. (*Meter and Instrument*).
S. R. SIVIOUR (*Transmission*).
A. J. GILL, B.Sc.(Eng.) (*Wireless*).

Secretary.

P. F. ROWELL.

Assistant Secretaries.

F. W. HEWITT, M.Sc.; A. E. RAYNER.

LOCAL CENTRES AND SUB-CENTRES.

ARGENTINE CENTRE.

Chairman.—C. G. BARKER.
Hon. Secretary.—R. G. PARROTT, Tucuman 117, Buenos Aires.

CHINA CENTRE.

Chairman.—S. FLEMONS.
Hon. Secretary.—W. MILES, c/o Shanghai Telephone Co., P.O. Box 1193, Shanghai, via Siberia.

IRISH CENTRE.

Chairman.—J. W. O'NEILL.
Hon. Secretary.—R. N. EATON, 1, Foster Place, College Green, Dublin.

MERSEY AND NORTH WALES (LIVERPOOL) CENTRE.

Chairman.—E. L. MORLAND.
Hon. Secretary.—W. PARRY, M.Eng., "Scaur," Birkenhead Road, Gt. Meols, Hoylake, Wirral, Cheshire.

NORTH-EASTERN CENTRE.

Chairman.—F. A. ORCHARD.
Hon. Secretary.—L. MELLOR, "Burn Brae," Heworth, Gateshead, Co. Durham.

Tees-Side Sub-Centre.

Chairman.—H. H. MULLENS.
Hon. Secretary.—H. SHAW, "Glenholme," Boosbeck, Saltburn, Yorks.

NORTH MIDLAND CENTRE.

Chairman.—J. W. ATKINSON.
Hon. Secretary.—K. C. COOP, B.Eng., 36, Park Place, Leeds, 1.

Sheffield Sub-Centre.

Chairman.—H. W. KEFFORD.
Hon. Secretary.—A. C. BOSTEL, 23, "Stumperlowe," Stumperlowe Lane, Sheffield 10.

[*Continued on page (III) of Cover.*

19 FEB 1965

RECENT PROGRESS IN POWER RECTIFIERS AND THEIR APPLICATIONS

By W. G. THOMPSON, Ph.D., B.Sc., Associate Member.

(*Paper first received* 2*nd November*, 1937, *and in final form* 1*st July*, 1938; *read before* THE INSTITUTION 17*th March, before the* NORTH-EASTERN CENTRE 28*th March, before the* SOUTH MIDLAND CENTRE 4*th April, and before the* TEES-SIDE SUB-CENTRE 6*th April*, 1938.)

SUMMARY

The paper gives a general survey of the present stage of development of power rectifiers. Recent innovations in the design of rectifier types are described, and some of the limitations are discussed.

The subject matter mainly concerns rectifiers of the mercury-arc type, including water-cooled rectifiers, glass-bulb rectifiers, pumpless air-cooled steel-tank rectifiers, and igniter types. These various rectifiers represent a voltage range from 200 volts to 50 kV (d.c.), and currents up to about 10 000 amperes. Reference is also made to some of the leading non-vacuum rectifiers, such as jet-wave rectifiers, gas-cooled arc types, and electrolytic and mechanical types. Most of these are still in course of development, and an indication of the progress achieved is given. The more direct methods of controlling the output of the mercury-arc rectifiers by means of control grids are mentioned, and in this connection voltage regulation, inversion, and arc suppression, are discussed.

General features of rectifier equipment are considered, together with some aspects of rectifier auxiliaries. The scope and performance of rectifier installations are also indicated, special reference being made to railway electrification, high-voltage working, and the applications of grid control.

Finally, some suggestion of the possible trend of future developments is given.

CONTENTS

(1) Introduction.
(2) Classification of Rectifier Types.
(3) Commercial Designs and their Auxiliaries.
(4) Experimental Types.
(5) Grid Control.
(6) Considerations of Rectifier Equipment.
(7) Scope and Performance of Rectifier Installations.
(8) Conclusions.

(1) INTRODUCTION

The introduction of the arc rectifier into power engineering may be considered to mark the beginning of a new stage in electrical development. Not only has the engineer had to extend the scope of his technical knowledge to include a field of electron phenomena hitherto regarded as subject matter for the physicist, but he has also had to adapt to engineering practice much of the vacuum technique of the physical laboratory. The steady progress of rectifier installations during the last 20 years is indicative of the effective manner in which the new knowledge has been applied. Some outstanding assets of the rectifier are its static nature, robust construction, efficiency, and low cost. The extent to which these factors have influenced the selection of rectifier converting plant can be seen from the growth of installed rectifier kW during recent years. This demand has been steady and progressive and shows no immediate signs of diminution; over 4 million kW of rectifier plant is in operation throughout the world.

With a preponderance of installed rectifier plant, competition ceases to be between rectifier and rotating machinery, and is now between different types and makes of rectifier. From the technical standpoint every detail needs consideration; the reliability, efficiency, and manufacturing costs, have only very narrow margins in which further improvements can be effected, so that for any given application the merits and suitability of the rectifier equipment as a whole require careful study.

With one or two exceptions, recent progress in rectifier practice has been by way of improvement and simplification of existing types, rather than the result of innovations. It is true that novel principles have been applied in connection with the more experimental equipments, though some years may elapse before they become adopted in practice.

The objects of the present paper are, to give a general account of the more notable developments in connection with rectifiers, and to discuss the scope of the available types of rectifier plant in relation to present-day requirements.

(2) CLASSIFICATION OF RECTIFIER TYPES

To appreciate the present position, it must be recognized that at the moment power rectifiers are divided into two main groups:—

(*a*) Vacuum, or more strictly low-pressure vapour, apparatus.
(*b*) Non-vacuum types.

By far the greater amount of the installed equipment is of the vacuum type, but much active experimental work is being carried out on alternative forms of rectifier. It is by no means certain that the present almost exclusive use of vacuum equipment will persist indefinitely in the future. On the other hand, it must be admitted that the position of the mercury-arc rectifier is an extremely strong one.

Power rectifiers of the first group are all of the mercury-vapour type, and are met with in several forms:—

(i) Hot-cathode rectifiers.
(ii) Air-cooled mercury-pool types.
(iii) Water-cooled mercury-pool types.
(iv) Igniter types.

The first group favours either glass or glass-and-metal construction of the vacuum vessel; the second all-glass or all-metal. All-metal is preferred in the third group, while the igniter can be either of glass or of metal construction. Of these different groups, the air-cooled all-metal design and the igniter types represent the most recent progress in their respective fields. An attractive feature of the mercury-vapour device is the possibilities of so-called grid control. This is dealt with in a subsequent Section, but it may be mentioned in passing that this has been applied in the first three groups with the object of retarding the striking of the power arc in the rectifier until a desired moment in each half-cycle. The igniter type, however, embodies the reverse process, and positive means are taken to ignite the arc at the desired moment with respect to the a.c. wave.

In general the common-cathode types classified under the second and third headings are more particularly suitable for continuous heavy-current working, but as a result of the voltage/current characteristic the maintenance of the cathode spot at light-load periods has to be assisted by auxiliary anodes. There are many instances where the various types overlap in their working range and may be regarded as competitive.

Considering now the non-vacuum types, these may be listed as follows:—*

(i) Mercury-jet apparatus.
(ii) Gas-cooled arc types.
(iii) Hydrionic convertors.
(iv) Mechanical rectifiers.

Most of the non-vacuum rectifiers are merely synchronous interruptors and are free from polarity limitations, but generally involve numerous auxiliaries or rapidly-moving parts. On the whole their efficiency, reliability, and economy, are lower than those of the mercury-vapour devices.

It has been found possible in most of the non-vacuum rectifiers to produce the analogous effect to "grid control" featured in the mercury-arc rectifiers. The action is usually of a positive type, since the initiation of the conducting period is dependent upon auxiliary means and not upon removal of the screening effect of the grid. It is only necessary to advance or retard the timing of the auxiliary ignition device to produce the corresponding change at starting of the conducting period in the working portion of the cycle. The mechanical inertia associated with the moving parts of these types of rectifier does tend to produce commutation difficulties, especially when inverted operation is attempted. Partly for this reason the application of an auxiliary supply to give so-called harmonic commutation has been put forward in several instances.

(3) COMMERCIAL DESIGNS AND THEIR AUXILIARIES

Hot-Cathode Rectifiers

Although fundamentally it is easier to obtain very heavy currents from a mercury-pool cathode, technical advances have made it possible to make hot-cathode rectifiers for outputs up to 275 amperes at 7 500 volts. At the other end of the scale, hot-cathode rectifiers have been produced for X-ray applications which have outputs of several hundred milliamperes at 100 000 volts.

The most common use at the moment is for anode supplies in wireless stations, and for such work there is a series of rectifiers giving an output of 1 000 volts, 500 milliamperes, up to 20 000 volts, 20 amperes. There are several sets in operation at various radio stations delivering about 10 kV, 10 amperes, from a 3-phase full-wave circuit. The reliability of such equipments can be very high, arc-backs being met only at the end of life and the lives being of the order of 4 000 to 10 000 hours.

These rectifiers almost invariably employ oxide cathodes, owing to their great efficiency. The power taken by the cathodes varies considerably between different makers, but generally speaking a 3-phase full-wave equipment having an output of 12 amperes at 10 000 to 20 000 volts will have a total cathode power of about 600 watts. As is generally known, the anode-cathode drop when current is passing is about 8 to 14 volts.

Thus it is clear that such equipments have very high efficiencies.

Since the valves depend for their operation upon the presence of mercury, it is not surprising that they must be operated between certain limits of mercury pressure. Since the space within the valve is saturated with vapour from a quantity of liquid mercury, the mercury pressure depends on the temperature of the coldest part of the valve.

For the small tubes the temperature range is wide and no special precautions are needed in temperate climates. In the larger tubes, the range is often narrower than the temperature range of the enclosure in which they operate. In such cases temperature control must be employed, and this often consists of a system of air blasts directed at the base of the rectifiers.

The air is maintained at the required temperature by a thermostat and heater.

This type of valve can also be made with the anode system not exposed but completely enclosed in a glass vacuum vessel, but such valves are entirely dependent upon radiation for the dissipation of the anode losses, for the rating of the valves is correspondingly reduced. Mention might be made at this stage of a very interesting all-metal hot-cathode rectifier, designed for an output of 600 amperes at low voltage, but although this was brought out a year or two ago the line of development does not appear to have been continued.

Mercury-Arc Rectifiers

Notwithstanding the large number of mercury-pool-type rectifiers produced in recent years and the wide experience gained, the production of a successful design is a matter of compromise between the different variables involved.

Recent tendencies in the development of mercury-arc rectifiers are to extend the upper limits of voltage in the few cases where the demand exists, to render grid control as effective as possible, and to make further use of air cooling. The general trend of application is in the direction of operating convenient-sized units in parallel rather than employing large single units with numerous anodes. It is true that in certain cases rectifiers with 18 or more anodes are used, but this is done rather with a view to reducing the intensity of the anode loading than to obtain an enormous output from a single cylinder. The reasons for this will be discussed later.

---

* Strictly speaking, this list should perhaps include copper-oxide rectifiers, which in sufficient aggregate can give a large power output; to keep the paper within reasonable length, the term "power rectifiers" has been taken to apply to the individual units.

In the smaller sizes of rectifiers it has been found possible to dispense with a number of the auxiliaries, so that where conditions of space are limited the grouping of small units is often preferred to a more elaborate unit of large output. Thus, even in connection with fairly large-capacity substations, the air-cooled rectifiers are not without significance.

The air-cooled mercury-pool-type rectifier is manufactured both in the glass-bulb and the steel-tank forms. Completely sealed-off commercial rectifiers of the latter type are made in this country, and various foreign firms supply a limited range of air-cooled rectifiers fitted with the usual vacuum pumps.

Glass-Bulb Types

The glass-bulb mercury-arc rectifier has few auxiliaries, and the usual method of suspension is in steel cubicles. Various attempts have been made to increase the current output of these rectifiers, and attention has been directed to the theories underlying their design. To meet temperature requirements, heat-resisting kinds of glass are used, the various glasses having softening points from 650° C. to 1 100° C. and a coefficient of expansion of 140×10^{-7} per deg. C.; molybdenum anode-connections are fused through the glass. The anodes of a rectifier tend to reach a high temperature, and cooling of the glass anode-arms has received special study, but their diameter of cross-section is limited by de-ionization considerations. It has also been shown that internal cooling can increase the output of these rectifiers. This is not a practicable solution, and recourse has had to be made to improved fan design. The power to drive the fan, even for the largest sizes, does not exceed 1 kW, and in a given case the application of a fan increased the bulb output by 150 per cent. Improved ventilation has made units of 500 amperes d.c. output possible, while experimental units have even been loaded to 1 000 amperes. Despite these facts, however, the general policy appears to be that of de-rating the bulbs to more modest outputs for the sake of reliability. A mean current of 200 amperes per anode has been suggested as a safe working value.

Tests have shown that there is a useful limit to the size and height of dome for a given cathode area, the leading dimensions of a 400-ampere bulb being cathode diameter 14 cm., dome diameter 47·5 cm., and height 85·5 cm. The glass construction makes the attachment of additional cooling devices, such as radiators, baffles, etc., costly, whilst the imploding atmospheric load constrains the designs to spheroidal forms with a low surface/volume ratio. As the units are comparatively cheap, however, the economic policy is to add an extra bulb in parallel, rather than to elaborate the units to increase their output. The units are generally constructed with 6 anode-arms and with control grids, if required.

In the event of very large power outputs being required, it is necessary to arrange for a sufficient number of glass-bulb units to be mounted in parallel, and substation capacities up to 6 500 kW have been thus obtained.

Another line of glass-bulb development is in the high-voltage field, where these rectifiers have been made to operate at voltages up to 20 kV. This implies a reverse voltage of about 40 kV and calls for special arrangement of the grids in front of the anodes and a lengthening of the anode arms. The current rating of the rectifier is reduced to about 10 amperes, and the practice is to arrange 9 arms in each bulb, 6 of these being in use at any one time. Each anode consists of a short rod and is terminated with suitable electrostatic shields to meet the high-voltage conditions.

Mention might be made at this stage of one feature of the completely sealed-off rectifiers of the mercury-pool type where considerable ingenuity has been expended, namely the igniting of the rectifiers. To start a rectifier and to enable its auxiliary anode to pick up current, it is necessary to produce an electron-emitting region on the surface of the mercury-pool cathode with the aid of some form of electric discharge. The criteria of a suitable device for this purpose are that it shall be rapid and effective in action, without putting undue strain on the glass. Several methods have been developed from time to time, and amongst those which have survived and remain in use are:—

(i) Making use of a local circuit formed actually with the mercury, and introducing a heavy current in the circuit to break it under the combined action of fusing and pinch effect.
(ii) Introducing vertical motion in a small column of mercury to make momentary contact with an energized ignition electrode.
(iii) Using a bimetal strip which is heated and deflects.
(iv) Using an external solenoid coil to operate a flexible dipping electrode.

Steel-Tank Air-Cooled Rectifiers

The lower economic limit for the water-cooled steel-tank rectifier is about 1 000 amperes. It was recognized that if the efficiency could be maintained and the number of auxiliaries reduced, the steel tank would fulfil many applications for currents of the order of 500 amperes.

Commercial rectifiers of the air-cooled pattern with pumps have been produced in a very compact arrangement, but the general design adopted resulted in the current range in this rectifier being only about 170 to 400 amperes.* To save space the vacuum pumping gear is mounted on the same bedplate as the rectifier, but underneath the cylinder. A system of ducting constrains the cooling air to the walls of the cylinder.

Pumpless Rectifiers†

Attempts have been made over a number of years to produce a successful steel-tank rectifier that would not require pumping at intervals during its life. The early efforts failed, largely on account of welding difficulties and because of the absence of leakage-testing methods which could be used under ordinary manufacturing conditions. With improvements in welding, and in particular the development of the atomic-hydrogen welding process, coupled with a better understanding of the diffusion of gases through metal containers, it became possible to construct perfectly vacuum-tight vessels.

---

* *Brown Boveri Review*, 1936, vol. 23, p. 150.
A. Siemens and A. Bower: "Small Steel-Tank Mercury-Arc Rectifiers with Air-cooling," *Siemens Zeitschrift*, 1937, No. 17, p. 525.

† H. W. Richardson: "Electrical Progress and Development—Mercury-Arc Rectifiers," *G.E.C. Journal*, 1936, vol. 7, p. 7.

The problem of anode and cathode insulation had already been solved with the development of the vitreous-enamel seal (see Fig. 1), and the fitting of a suitable vacuum-tight sealing device rendered the all-metal pumpless rectifier a practical proposition. In order to determine whether the continuous " cleaning up " process resulting from the arc was essential to the effective working of the pumpless rectifier, one of the vessels was sealed off and operated after long intervals over a period of two years. No deterioration of the vacuum was found, so that the rectifiers are perfectly suitable for working where intermittent loading is likely.

The general arrangement of the pumpless unit is shown in Fig. 2. The unit consists of a central dome around which are arranged the anode arms and the auxiliary ignition anodes. As the result of the adoption of the side-arm construction with arm temperatures of over 200° C., a very effective dissipation of heat from the anodes can be obtained, thus permitting a high rating of the rectifier. The all-metal construction makes for robustness and ability to withstand mechanical shock, which is fully borne out in practice. In addition to this, it permits the oblate dome construction with a large surface/volume ratio, facilitates the external attachment of radiators and air baffles, and renders possible the provision of internal cooling ducts if required. Thus, with the pumpless steel-tank rectifier it does become economic to increase the rating per cylinder and so obtain an increased output per unit floor area. To effect the necessary dissipation of heat from the walls of the vessel, use is made of a system of ducting through which cooling air is forced under pressure of a fan. The power dissipated varies over the active portion of the surface from 2 to 6 watts per square inch of cooling area, and recent improvements have resulted in a more simple, yet equally effective, arrangement of air ducting. Because of the absence of heavy metal parts and cooling liquid, the air-cooled rectifier soon reaches its normal working temperature, perfectly reliable starting being obtainable

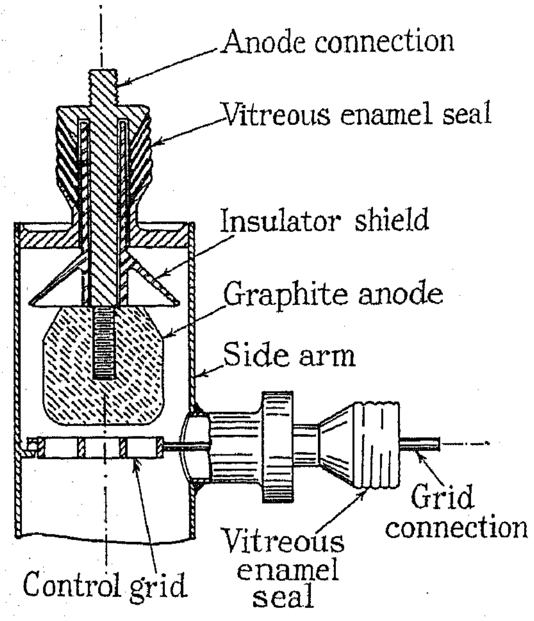


Fig. 1.—Victric seal assembly for grid control of pumpless rectifier.

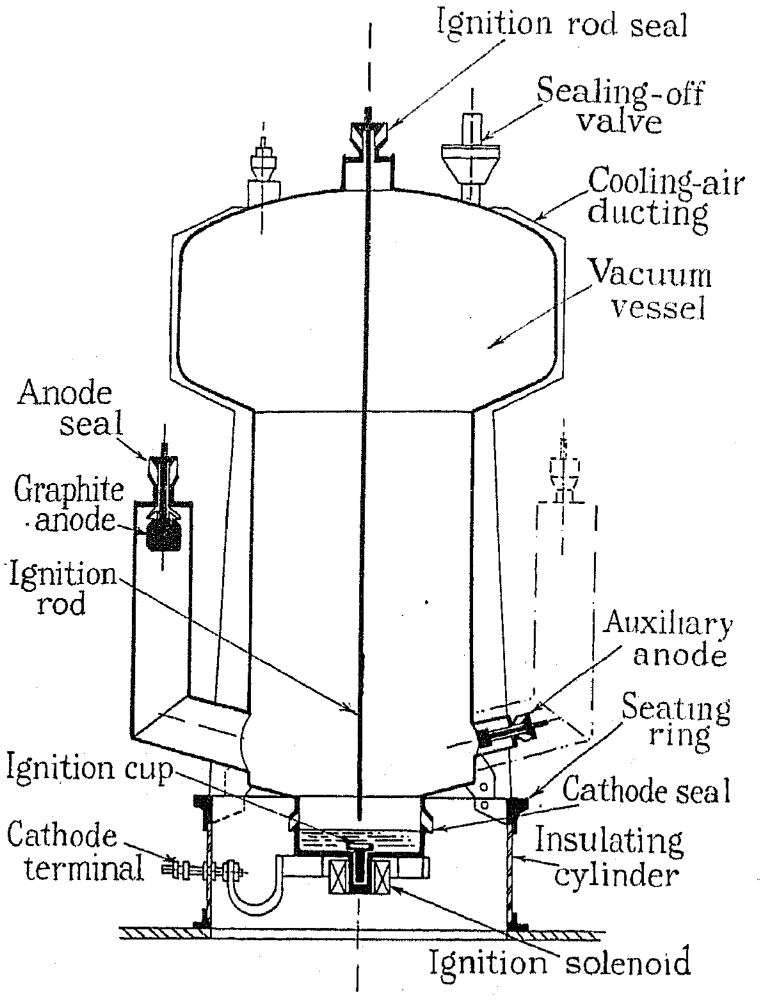


Fig. 2.—Arrangement of pumpless air-cooled steel-tank rectifier (600 volts, 550 amp.).

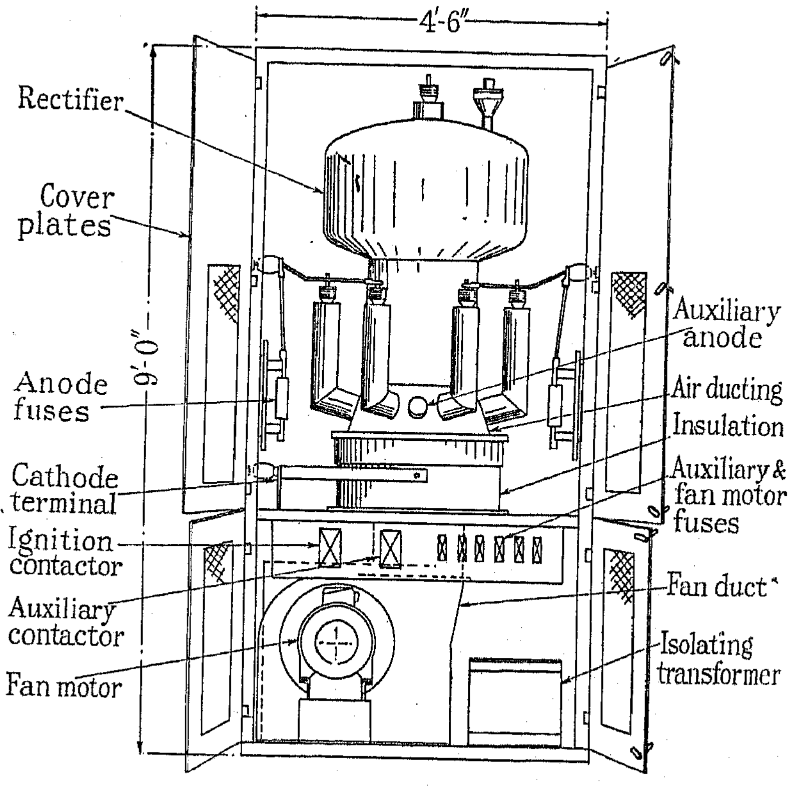


Fig. 3.—Typical arrangement of air-cooled rectifier in cubicle.

from 3° C. The initial striking of the arc is effected by locally lowering the surface of the mercury with a solenoid-operated cup so as to break contact with a fixed ignition electrode.

Rectifiers in the typical cubicle arrangement shown in Fig. 3 have been supplied in large numbers and various sizes, with and without grid control, for current outputs from 250 to 750 amperes, while outputs of 1 000 amperes have been obtained under test conditions. As a further test a 20 000-ampere short-circuit was applied to one of these units without ill-effects. The fan and the auxiliary ignition constitute the only auxiliary power demand of this type of rectifier, so that its overall efficiency is very high. Most of the pumpless rectifiers are in service at d.c. voltages of about 500 volts, but the units have been proved suitable for operation at 3 000 volts if required. Incidentally, it is possible to obtain an output of 1 500 kW at 1 500 volts, using only two cylinders in parallel. The question of still higher working voltages is merely one of lengthening the anode insulators to suit the new conditions.

Steel-Tank Water-cooled Types*

There have been few changes in recent years in connection with steel-tank water-cooled rectifiers, but passing reference will be made to some of the leading features.

The whole of the working parts of the rectifier are enclosed within the vacuum vessel, the internally situated anodes being screened from one another by cowls which may be either connected to the tank or insulated therefrom. Improvements and compromise in design and proportioning of the cowls have made possible reliable operation over a wide temperature range down to 5° C. At the other end of the scale, internal water-cooling coils are often used to facilitate the dissipation of heat from the rectifier. Their application is directed more to permitting an increased output from a standard size of tank so as to avoid having to introduce too many tank sizes to cover the usual range of specifications. By way of example, a unit nominally rated at, say, 1 500 kW can be loaded up to 2 000 kW by this means.

Certain corrosion problems have been encountered in water-cooled rectifiers, and because of " pin-hole " effects and stray currents the usual anti-corrosive coatings have not been entirely successful. Where conditions are serious, the introduction of metallic salts such as dichromates is advocated. When dissolved in the cooling water these induce a passive state at any exposed iron surface, thus limiting leakage currents.

The outstanding differences in construction of the various makes of water-cooled rectifier are the methods of sealing-off the current leads, the means of anode cooling, and the design of the grids. Seals used in connection with mercury-arc rectifiers may be divided into two groups, one consisting of the seals which also serve as insulators, the other comprising the mechanical seals having a length of porcelain tube for insulating purposes. Examples of the first group are the vitreous-enamel and the micalex seals, while the second group includes the mercury seal, the rubber seal, and the soldered seal.

Briefly, the vitreous-enamel seal, shown in Fig. 1, consists of a number of thin metal cones enamelled all over and fused together to form an insulator of the desired dimensions. Such an arrangement has remarkable electric strength and excellent mechanical properties —the dimensions being governed by flashover and not puncture consideration. Insulating seals made up in this fashion now range from small 2-cm. diameter seals for grid leading-in insulators and vacuum-gauge mountings, to 50-cm. diameter insulators necessary for insulating the container for the mercury-pool cathode. Careful oven-temperature control has resulted in the production of very reliable seals of this type. Though the practical limitation is the temperature gradient across the seal itself, it has been found possible to run the rectifier top-plates, on which these seals are mounted, at a temperature of 120° C. without damaging the seal. In actual practice the rectifier top-plate temperature rarely comes within 40 deg. C. of the figure mentioned, so that the factor of safety under working conditions is very high. One of the advantages of this type of seal is that it becomes possible to arrange for air cooling of the anodes and permit the use of a smaller and more robust radiating element on the anode stems. It also enables temperatures of about 80° C. to be used for the degassing of the rectifier during manufacture.

In the case of the mercury seal, the joint is maintained under a head of mercury, and visible means are provided to ensure that the head of mercury is maintained at the proper level. The rubber seal is a simple mechanical arrangement embodying a metal-faced rubber gasket, and, while this joint can hardly be said to be so permanent as the other two types, experience has proved it to be practicable and free from leakage. These types of seal permit the use of single long porcelain tubes for the anode bushings of higher-voltage rectifiers, giving a somewhat cheaper form of bushing than the vitreous-enamel type at high voltages. In the case of the mercury and the rubber seals, the operating temperatures should not exceed 80° C., and the use of water cooling for the anodes is customary with heavy current ratings.

The soldered seal is effected by soldering a copper ring directly to the porcelain bush, the ring being sealed tight to the cover plate. An example of this seal is shown in Fig. 6.

Various types of cathode insulator are in use, the chief being the multi-cone vitreous-enamel seal and another —the porcelain-ring type. In the smaller rectifiers using the vitreous-enamel seal, no additional external fitting is now required, but with the porcelain rings and the large-diameter vitreous-enamel types use is made of a clamping ring with spring-loaded bolts to maintain a uniform compressive stress under all conditions of loading and temperature.

Recent anode construction is typified by the almost universal adoption of graphite instead of steel anodes; this is largely due to the good qualities of the graphite at the working temperature of 600° C., and in particular the low thermal conductivity, the high fusing point, and the absence of sputtering. It is also effective in the construction of high-voltage rectifiers. Both the mercury and the oil cooling of the anodes have been abandoned, but the air cooling by means of radiating fins clamped to heavy copper anode stems appears to be gaining ground compared with the thermo-syphon water-cooled arrangements using large air-cooled water-filled radiators.

---

* J. C. Read: "The Application of the Mercury-Arc Rectifier to Heavy Engineering," *Proceedings of the Rugby Engineering Society*, 1934, vol. 28 (2), p. 1.

Mention may be made of the various arrangements of grid adopted for promoting the rapid de-ionization of the space in front of the anode needed to impart to the rectifier the high dielectric recovery rate required for polyphase operation. This action of the grids is distinct from the grid-control functions which will be discussed later. In the present connection, the graphite grid is being progressively adopted in place of the steel and high-melting-point metal types.

In some cases it is considered that a non-conducting material, such as quartz, forms a superior de-ionizing surface, and grids of this material have actually been used. Both the concentric and the louvre types of grid have been found effective in practice. The grid design is largely a problem of providing the optimum conditions in the clearance space between the grid and the anode, where voltage gradients up to 2 000 volts per cm. have been successfully dealt with. The minimum clearance appears to be limited by auto-electronic emission due to local intensification of the surface field.

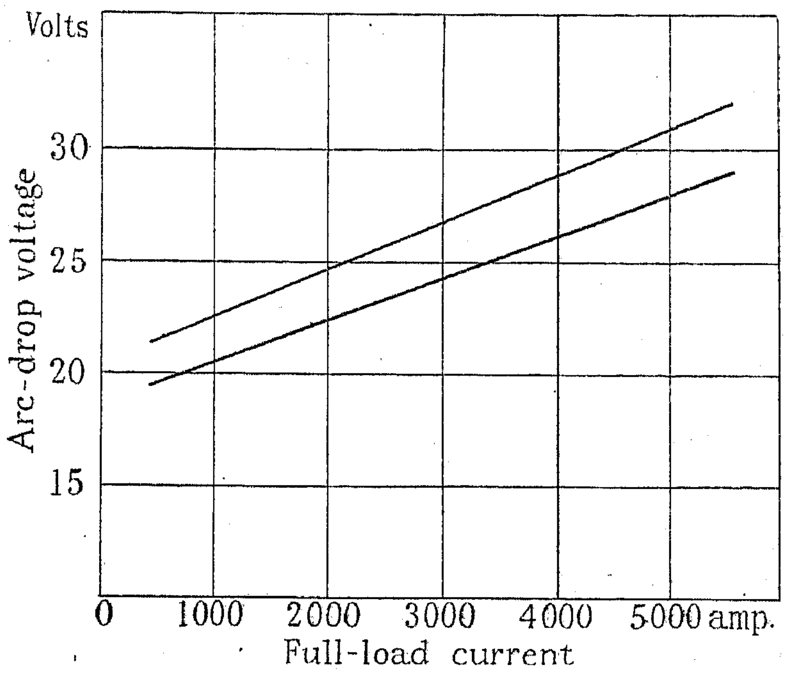


Fig. 4.—Arc drop at full load for different tank sizes. Limits of commercial designs.

As a result of the foregoing developments, it has been found possible to construct thoroughly reliable rectifiers up to 6 000-ampere ratings, and, should the demand arise, 10 000 amperes d.c. output could easily be obtained from a single tank. It must be admitted, however, that the enormous current ratings of 16 000 amperes mentioned a few years ago have not proved advisable. The use of a larger tank involves a longer arc path and also high losses, as indicated by the arc-drop/tank-size curve shown in Fig. 4. On the other hand, it has been found possible to extend the working voltage of rectifiers up to 50 kV, but here the gain in voltage output can only be obtained by drastically de-rating the current output from a given tank size. Fig. 5 shows how the increase in the voltage rating severely limits the current loading.

Whilst dealing with the size of rectifiers, a consideration of the sectionalized type of rectifier used in America may be of interest. The makers claim that the economic balance between efficiency, reliability, and cost, has an optimum value corresponding to rectifier sizes ranging from 1 250 to 3 000 amperes, as compared with the usual 5 000 amperes for large units. The assembly of the cellular units is facilitated by making each section complete in itself, i.e. with all auxiliaries mounted on the rectifier, the whole being contained in an earthed cubicle. Larger outputs are obtained by adding further units in parallel, so that the voltage-drop is always maintained at about 23 volts as compared with a probable 30 volts for a very large unit. The sectional rectifier has made little headway in Europe, owing mainly to the different viewpoint and manufacturing tendencies. With the introduction of the air-cooled pumpless rectifier, whose outputs per cylinder are rapidly approaching the values suggested in connection with the sectionalized system, the position becomes altered and the sectionalized system might well be applied to give not only increased efficiency but a considerable saving of weight and space, using pumpless steel-tank rectifiers.

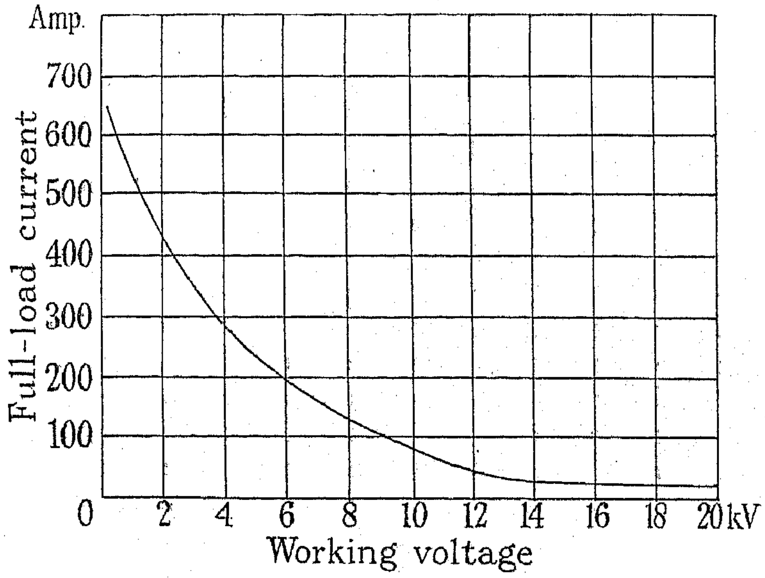


Fig. 5.—Influence of working voltage on current output of rectifier.

Igniter Units

These units, of which the so-called "Ignitron"* is the chief example, represent a recent phase in the development of the mercury-arc rectifier. The polyphase ignitron is made up of an assembly of single-phase units each provided with an igniter rod of semi-conducting material such as boron carbide (silicit) inserted permanently in the mercury (see Fig. 6). At the instant of ignition the ignition circuit receives a current impulse, and the resulting voltage field, produced by the concentration of the current at the junction of the igniter rod and the surface of the mercury, is sufficiently intense to give rise to a cathode spot which allows the power arc to form. Actually, the time-lag on the formation of the main arc is less than 100 microseconds. The ignition principle is remarkable in many ways; it is, for example, still effective at − 200° C., though it does not follow that a stable arc is produced at these low temperatures. A further improvement has been the slotting of the igniter electrodes to give a reduced starting current at a slightly higher voltage. The ignition is timed with the aid of small grid-controlled mercury-vapour rectifier circuits, and these would be conveniently excited from a synchronously-driven induction generator. The diagram of connections is shown in Fig. 7, from which it will be seen that the ignition is dependent upon the proper functioning of the continuously running auxiliary valves.

---

* D. Parkhard and J. Hutchings: "Sealed-off Ignitrons for Welding Control," *Electrical Engineering*, 1937, vol. 56, p. 37. J. Slepian: "The Ignitron—A New Mercury-Arc Power Converting Device," *Electric Journal*, 1936, vol. 33, p. 267.

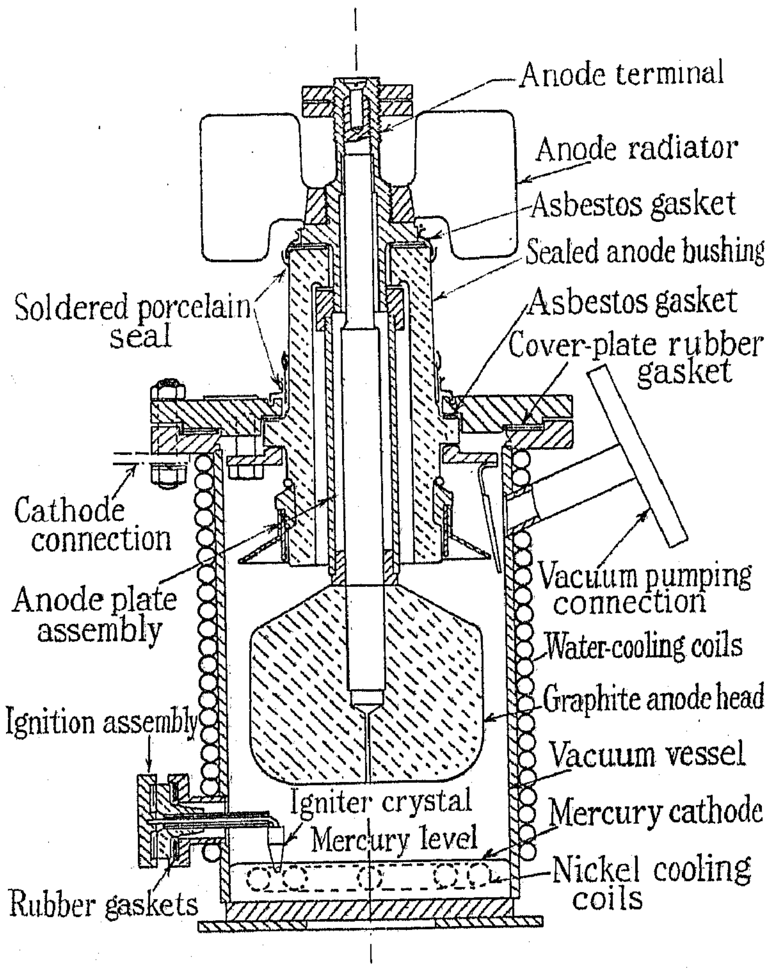


Fig. 6.—Ignitron single-phase rectifier.

Ignitron experimental development has taken two main directions, the first constituting single-phase units for half-cycle welding, and the second an ordinary controlled rectifier proposed for industrial purposes. The Ignitrons are made both in pumped and in sealed-off designs; the former are atomic-hydrogen welded and bolted together, while the latter are electrically seam-welded and sometimes copper-brazed. Light internal parts are used to avoid prolonged pumping programmes. The sealed-off type has been made in units up to 250 amperes, and general use is made of the 75–100-ampere (mean) sizes, for which the output does not warrant the cost of a pumping system.

Fig. 6 shows the cross-sectional view of a rectifier fitted with the usual vacuum-pump connections, and rated at 250 amperes for electrochemical service. The chief attraction of the welding application is the controlled time-intervals through which the current can be allowed to flow. In the case of the half-cycle welding units, the problem has been the tendency of the cathode spot to travel outwards in the direction of the wall of the vessel, but this has been overcome by means of a suitably dimensioned cathode. Such units have been constructed for 500 volts and with peak current-densities up to 500 amperes per square inch. The small sealed-off welding Ignitrons are made with both glass and water-cooled metal containers. Hydrogen diffusion has been prevented by using stainless steel, while an iron-cobalt-nickel alloy (kovar) is used to effect connection to the glass seals. Outputs up to 7 000 amperes (peak) have been obtained from a group of Ignitrons, corresponding to about 100 amperes (mean) per valve.

The use of separate vacuum vessels for each anode-cathode pair means that there is an absence of ionized vapour between the electrodes during the reverse half-cycle, so that a close electrode spacing becomes possible. Advantage can be taken of this fact to produce low-voltage polyphase Ignitron rectifiers with about 13·5 volts arc drop at 300 volts where shielding can be largely dispensed with. As a result of this, it is possible to apply this type of apparatus economically to a.c. voltages as low as 200 volts. At 600 volts there is need for shielding and the arc drop becomes increased, while at still higher voltages the arc drop approaches the normal value for a mercury-arc rectifier, and so far as efficiency at the higher voltages is concerned the difference is practically negligible. Incidentally, Ignitron rectifiers have been operated at 16 kV with the current reduced to 5 amperes.*

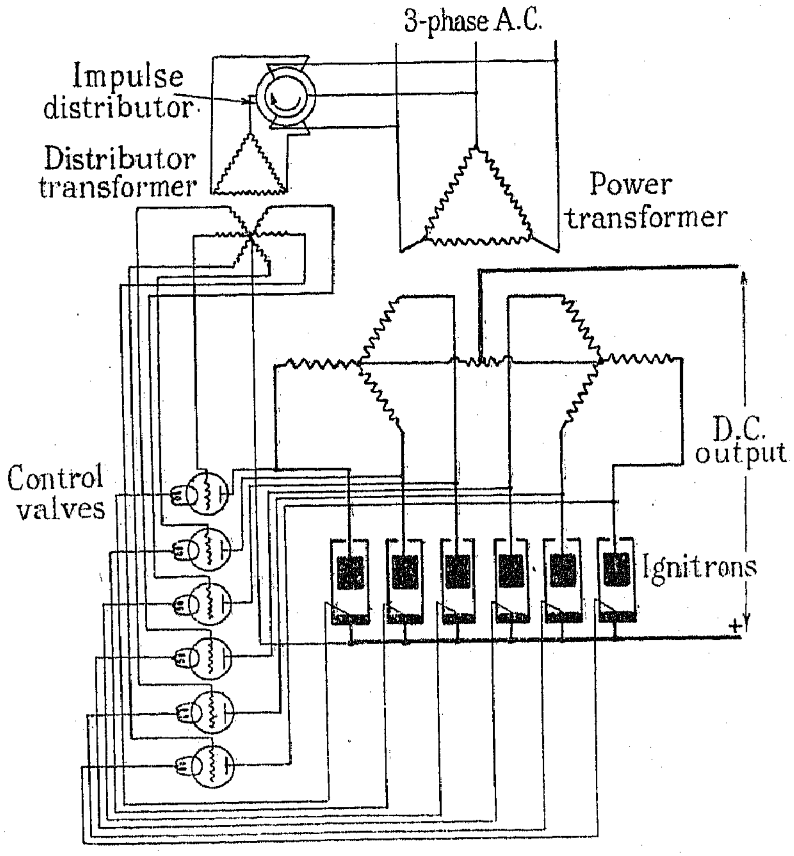


Fig. 7.—Main and auxiliary circuits for Ignitron rectifier.

---

* C. B. Foos and W. Lattemann: "High-Voltage Mercury-Pool Tube Rectifiers," *Proceedings of the Institute of Radio Engineers*, 1936, vol. 24, p. 977.

Rectifier Auxiliaries

It is not possible in this paper to deal at length with the wide subject of rectifier auxiliaries, but some notes will be given on a few outstanding features thereof.

Ignition.

Both a.c. and d.c. ignition systems are available, the tendency being to standardize whichever of the two systems is already in use on a given scheme. The d.c. method has some practical advantages, inasmuch as the ignition gear is not constrained to open in the correct half of the working cycle before proper ignition can result.

Vacuum Pumping System.

Vacuum pumping practice appears to be more or less standardized, although the various makes of preliminary vacuum diffusion pumps differ slightly in construction. Under ideal conditions it is possible to produce pressures as low as 0·1 mm. with the rough vacuum pump, but the mercury-vapour diffusion pump is still necessary to reduce the foreign gas pressures of 1 micron at which the rectifiers usually operate. The actual mercury-vapour pressure may, of course, be higher. Two forms of heater are available for diffusion pumps, the a.c. single-turn transformer type and the resistance heater. The former is preferred on the grounds of longer life, but the latter can be used with alternating or direct current and is more convenient to demount if necessary.

The control and measurement of vacuum is essential for the successful working of the water-cooled rectifier. Two types of vacuum gauge are available, namely the McLeod compression gauge and the Pirani hot-wire equipment. The Pirani gauge, based upon the Wheatstone-bridge method of measurement, indicates the pressure by recording the thermal conductivity of the residual gases. Both types of gauge have been recently improved, the McLeod gauge being now available in a more compact form, while the Pirani gauge has been provided with improved mounting and the use of the vitreous-enamel seal in its construction. Incidentally, the latter gauge is also employed to operate the vacuum relays associated with the water-cooled rectifier.

Cooling.

The cooling systems used in connection with the water-cooled rectifier have remained substantially unchanged, the water being circulated through the rectifier water-spaces to the heat exchanger by means of a centrifugal pump. Thermostatic valves, operating on the bimetal-strip principle, provide a convenient means of regulating the flow of cooling liquid.

Thermosyphon cooling, or a normal mains water supply, or a small circulating system, is employed for the diffusion pump and the water-cooled valve connecting the rectifier to the vacuum pumping system. Alternatively the valve may be air-cooled if desired.

(4) EXPERIMENTAL TYPES

While they have not reached the stage when general application can be made, the non-vacuum rectifiers have made considerable progress in recent years. Although much development still remains to be done, some notes on these types may be of interest.

Mercury-Jet Types*

Development work continues to be carried out on the mercury-jet types of rectifier, and a new testing laboratory for this purpose, with testing facilities up to 1 000 kVA, was inaugurated in Denmark in 1937.

Three types of mercury-jet rectifier have been proposed, the jet-wave rectifier, the jet-disc type, and the truncated-jet type. Most of the development work has been carried out on the jet-wave type, but the other two types are of considerable experimental interest. The jet-wave type, of which several descriptions have already been published, makes use of the synchronous lateral deflection of a mercury jet supplied with alternating current and subjected to a steady magnetic field. The free end of the jet is made to traverse current-collecting combs, thereby producing the synchronous switching action necessary for rectification. For polyphase working 3 single-phase units can be arranged with their jets in the proper phase relationship to produce correct phase commutation. Recent developments have been improvements in the auxiliary electrode systems which enable the current contact to be made with the minimum of distortion of the moving jet. These modifications have resulted in a raising of the possible current output from the jet to over 1 000 amperes. A 300 kW, 3 000-ampere, rectifier having 3 single-jet commutators is under investigation, and the output of each of these commutators has recently been increased to 125 kW. The general tendency is to reduce the number of jets for a given power output; at the same time the voltage on each jet can now be raised to 1 000 volts. The 200-kW jet-wave rectifier has already been successfully demonstrated on 500-volt tramway systems, and a 1 000–2 000-kW traction rectifier is under consideration.

An important feature of the jet-wave rectifier is its efficiency at low voltages. Above the 500-volt range there is little to choose between this and the other rectifiers, but in the range from 50 to 200 volts its overall efficiency remains at the comparatively high values of 90–94 %. Tests have shown the rectifier to have a good overload capacity and to be capable of withstanding short-circuits, while more recently the possibilities of inverted operation of the jet-wave rectifier have been demonstrated.†

Gas-cooled Arc Types‡

The gas-cooled arc types have passed through a number of experimental stages during the past few years and have now regained much of their original simplicity, as will be seen in Fig. 8. The chief features of these valves at the present time are the straight-through axial air flow and auxiliary arc ignition. The power arc burns between two main electrodes which are provided with screen electrodes to decrease the intensity of the electrostatic field of the reverse voltage in the heated region of the arc-foot point. One of these screen electrodes is insulated and serves also as an ignition electrode. An ignition voltage of about 5 kV is sufficient to break down the gap between the ignition electrode and its main electrode, and thus the current for the auxiliary arc is now obtained direct from the power transformer. The auxiliary arc is produced at one electrode system, is carried across to the other electrodes by the air flow, and initiates the power arc between the two main electrodes. The power arc in turn commutates the auxiliary arc, thereby restoring the small insulating gap between the main and the ignition electrodes. The auxiliary arc may be at either the anodic or the cathodic electrode. Thus the reversibility of the power flow is not impaired, and the polarity of the valve will depend upon the half-cycle in which ignition takes place.

---

* J. HARTMANN: "The Jet-Wave Rectifier," *Journal I.E.E.*, 1930, vol. 68, p. 945, and "The Jet-Wave Commutator as means for the Production and Conversion of Heavy Direct Current, Large Power, and High Voltage," *Archiv für Elektrotechnik*, 1935, vol. 29, p. 855. J. HARTMANN: "The Plate Jet" (G. E. Gad, Copenhagen, 1935).

† W. E. FRENCH: "High-voltage D.C. Transmission," *Electrical Review*, 1936, vol. 118, p. 47.

‡ E. MARX: "Arc Convertors" (Julius Springer, Berlin, 1932). W. G. THOMPSON: "The Application of a Gas-cooled Arc to Current Conversion," *Journal I.E.E.*, 1934, vol. 75, p. 603.

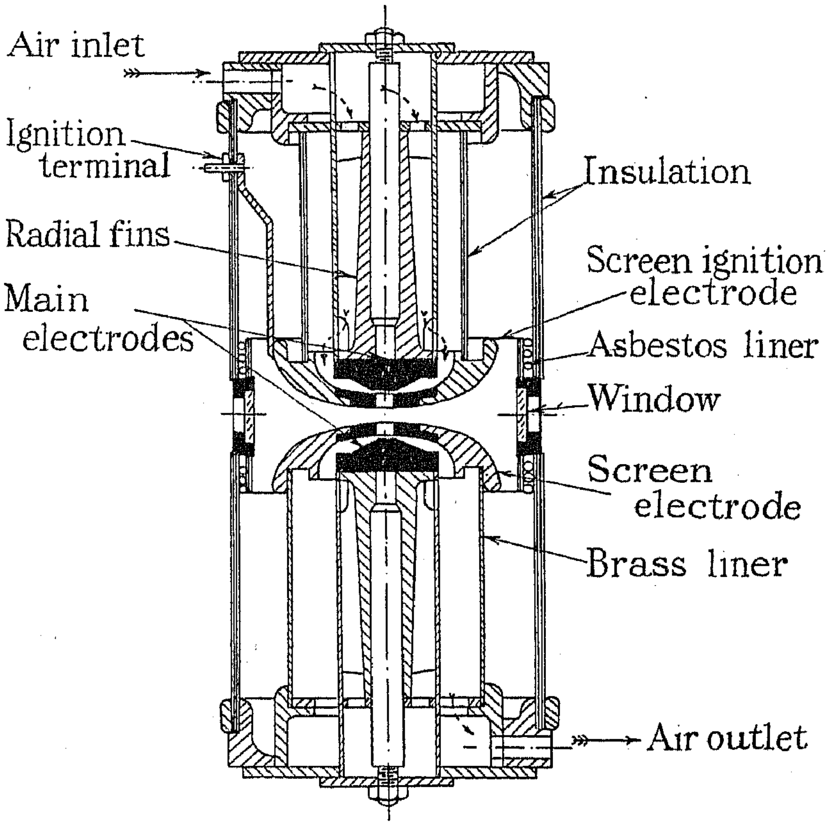


Fig. 8.—Sectional elevation of Marx-type valve.

The quenching of the power arc occurs at the current zero under the combined cooling and scavenging action of the air flow. The rate of recovery of the electric strength of the valve under heavy current has been measured by high-speed oscillograph methods and appears to meet all practical requirements. The valves have been operated successfully at heavy currents up to 2 000 amperes (peak), and at moderate voltages, and at very high voltages (i.e. 300 kV) and light currents. Effective use of circulating air under a pressure of about 10 atmospheres enables high reverse voltages to be withstood at practicable electrode-spacings. The arc-voltage/load-current curve has a drooping characteristic falling to about 70 to 100 volts at about 100 amp. d.c. output. This is somewhat high, but the arc voltage represents a negligible loss with the valve operating at several kV. The problem of electrode erosion is still under investigation. Considerable improvements have been made by the use of extended electrodes, and electrode lives of some thousand hours can be obtained. The momentary overload capacity is usually 10 or more times the normal full-load working current. The operation of the valve can be stopped immediately by cutting off the ignition, while by adjusting the ignition the power output of the valve can be limited as desired. The valves have been operated in 3-phase and 6-phase circuits as a rectifier, and also as an invertor. In both cases the operation has been satisfactory, and so long as the conditions necessary for phase commutation are maintained there is no difficulty. With electrode separations corresponding to a nominal breakdown voltage of 30 kV (peak) these valves have been operated satisfactorily at atmospheric pressure with reverse voltages of over 20 kV (peak) in a 3-phase circuit. The factor of safety would be obtained by raising the air pressure rather than by increasing the electrode separation. The general tendency for development at the moment is towards high voltages and moderate currents, but the application of these valves is largely a question of suitable opportunity arising.

Hydrionic Rectifiers*

These rectifiers, of which many widely different experimental forms have been produced, appear to be most suitable for operation at moderately low voltages. The arrangement in every case is such that during the conducting period the current is carried by an electrolyte. In order to deal successfully with the leakage on wetted insulating surfaces, the more practicable designs arrange the electrolyte in the form of high-speed jets. One form of this rectifier makes use of a synchronously rotating arm cutting into an equally spaced group of jets corresponding to the number of phases on the transformer. The voltage-drop of such a rectifier is dependent upon the nature of the electrolyte used and the effective design of the nozzle in the moving part which completes the circuit through the jets. By careful design and the provision of large electrode-areas and small clearances, voltage-drops below 10 volts with currents of 500 amp. have been measured.

There still remain a number of problems to be solved in connection with these rectifiers, notably the handling of the alkaline caustic electrolytes used and the electrolytic gases evolved. The temperature coefficient of resistance of the electrolytes also requires careful study. An interesting phenomenon in this type of rectifier is the sparkless break at commutation, which may be ascribed partly to the difficulty of the cathode-spot formation and partly to the high resistance of the liquid path at the point of breaking.

(5) GRID CONTROL

In reviewing the progress made in connection with the so-called "grid control" for rectifiers, it must be admitted that the extent to which grid control has been applied in practice has fallen considerably short of the experimental and theoretical possibilities. As a means of controlling the output voltage of the rectifier in a continuously smooth manner, grid control appears to be admirable. On the other hand, it involves several important practical points; first the suitability of the grid control gear, and secondly the cost of the filter gear necessary to cope with the large-amplitude harmonics produced in the voltage output wave, when the ignition or the start of the conducting period is retarded. Another point would be the poor power-factor resulting when operating at reduced voltage under grid-control conditions. So far as the mercury-arc rectifier is concerned, grid control has been limited to the inhibition of the striking of the power arc. It is true that on a small experimental scale it has also been found possible to stop the arc discharge once it has been started, but so far as the author is aware there have been no major practical developments of this idea. On paper there are many attractive forms of grid control to produce certain desired characteristics, and many methods of frequency-changing, but in actual practice it would appear that this application may be limited to the voltage regulation of rectifiers, inversion in connection with regenerative braking, and arc suppression.

---

* British Patents Nos. 447095, 453080, November 1934.

The Grid-Controlled Rectifier

The grid-controlled rectifier is of normal construction except for an extra insulated grid situated immediately in front of each anode and connected to a source of negative d.c. potential which persists except when the positive debiasing influence is applied. There still remains considerable scope for research into the mechanism of the action of the control grid in relation to the arc stream, but much more is known about the grid characteristics and their behaviour under given conditions of rectifier loading and temperature. It is known, for example, that there is an optimum temperature at which the grid is able to exercise its maximum shielding influence on the anode for the particular value of voltage bias applied. Furthermore, under extreme overload conditions the factor of safety on the grid control also diminishes unless the bias is suitably increased. The object of successful design is to adjust the stable portions of these characteristics to correspond to the working range of temperature and load on the rectifier.

It has been found advisable in the interests of precision to apply the debiasing voltage in the form of a steep-fronted wave, as the alternative method of steadily increasing the amplitude of the positive bias may lead to uncertain timing of the ignition of the anodes. A steepness of 60 volts per electrical degree is usually adequate. Various suggestions have been made as to the ideal profile of the positive impulse to be applied to the grid, and theoretical reasons have been advanced for prolonging the impulse to cover nearly all of the burning period for a given anode, the train of the wave being shaped away to cause a gradual transition from the positive to the negative bias condition. Practical experience has shown, however, that whilst it may be an advantage to prolong the impulse in certain circumstances, the working conditions, and in particular inverted operation, demand that the duration of the positive bias be kept within reasonable limits.

Voltage Regulation.

In the case of voltage regulation, the arrangement is that for the normal voltage the ignition of the rectifier must be slightly retarded; to increase the d.c. voltage the ignition of the rectifier must be advanced, and to lower the voltage the ignition must be further retarded.

Various methods of effecting grid control have been devised, which may be grouped as follows:—

(i) Those using synchronously-rotating mechanical parts, such as commutators or contact makers.
(ii) Those employing saturated transformer or similar wave-peaking devices.
(iii) Those using condenser discharging circuits.
(iv) Circuits employing thermionic devices.

In order to achieve the desired voltage regulation, it is necessary to vary the instant at which the impulse is applied. This can be carried out in three ways, namely by using phase-shifting transformers, altering the synchronous position of the rotating mechanical gear, or controlling the grids of the thermionic control device, depending upon which system is in use. All these methods have been tried out under practical conditions, though each has its distinctive features requiring careful design. It is also necessary to recognize the true nature of the problem of grid control. Many devices have been suggested in this connection, but the difficulty lies in producing the proper working characteristic. Most schemes devolve essentially into one of voltage regulation, rather than that of compounding. The inherent difficulty is that the curve of the mean output voltage of the rectifier under control conditions is a cosine characteristic, and it is practically impossible to devise simple means whereby the phase-shift actuated by the load can be translated into terms of a suitable voltage/current characteristic. We have also to distinguish between those cases where the rectifiers are operating independently and where they are operating in parallel with other equipments, such as rotary convertors, etc. The obvious solution appears to be to provide an external shunt characteristic to suit the rectifier, since the inclusion of voltage-regulating means and relays results in the action not being absolutely instantaneous where compounding is attempted.

Inversion.

Inverted operation of the mercury-arc rectifier is effected by changing over the polarity; the current must still flow in the same direction through the rectifier, and is made to flow by the impressed d.c. voltage against the back e.m.f. provided by the a.c. phases in their proper anodic sequence. An a.c. voltage supply is necessary for wave-forming, and the function of the grid control is to regulate the transference of the arc from one anode to the next at the proper instant. The same methods of control have been applied to the invertor as to the rectifier, the only difference being slight modifications to the characteristics and a change in the phase position of the ignition point.

Unfortunately, the invertor is still handicapped by the fact that it injects alternating current at a leading power-factor into the a.c. network, and as a result its usefulness is practically confined to regenerative braking in traction and rolling-mill operation. Another difficulty is the polarity change-over required. Where it is possible to regenerate to schedule, use can be made of change-over switches, but cases of emergency braking can only be dealt with by having a second rectifier permanently reverse-connected across the d.c. busbars. By this means the substation can supply or absorb energy in rapid sequence if called upon to do so.

Any of the four main types of grid-control schemes can be adapted to suit voltage-regulation or inversion requirements. Circuits have been recently devised to give automatic adjustment of the slope of the operating characteristic, the change-over point, and the limits of loading of the invertor.

Considering now examples of types of control gear, the operation of the synchronous distributor has been frequently described in the technical Press, and the means by which the positive impulses are applied to the negatively biased grids can be seen from Fig. 9.

Some practical notes may, however, be of interest. The most suitable form of distributor is that of a small commutator having two diametrically-spaced live segments; the remainder of the segments are idle and merely serve to avoid uneven wear. The brushes are suitably grouped around the commutator, and advance or retard of the ignition is obtained by brush-rocking. This method has proved more convenient than adjusting the synchronous position of the commutators because of the low inertia of the brushgear; the slight friction is also sufficient to prevent hunting, and overhauling can be avoided by the fitting of slipping clutches. A steady negative bias of about 100 volts and positive peaks up to 300 volts are used. Using good-quality brushes and avoiding sparking at the commutator, the method is perfectly reliable and the brush wear slight. Level-compounding can be carried out by making the device responsive to a voltage-regulating relay, but for parallel running and inverted working voltage-balancing devices involving electrical or mechanical differentials are used.

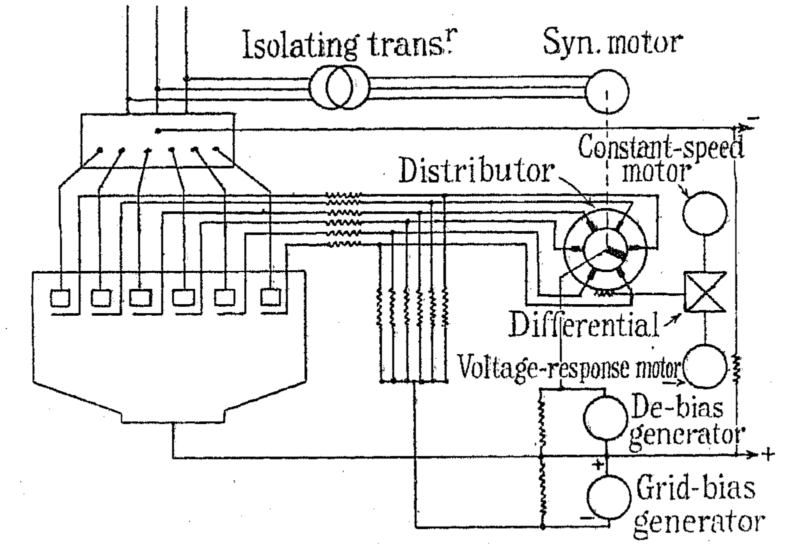


Fig. 9.—Grid-control circuit using synchronous distributor and voltage-regulator differential.

The application of a peaky wave transformer to grid control (Fig. 10) calls for a means of adjusting the phase of the voltage impulse to give the requisite variation of the ignition instant for voltage regulation, and the phase shift needed when changing over to inverted operation. One such system employs a phase-shifting transformer in series with the winding of the wave-peaking transformer. The rotation of the phase-shifting transformer can be achieved by means of a direct-current spring-opposed torque motor whose armature is supplied at constant voltage while its field carries some given amount of the output of the rectifier. Any desired characteristics can be arranged by rheostats connected in series with the motor armature, whilst further flexibility is also possible with the aid of additional shunt windings and screw adjustments. Owing to the inertia of the moving parts there is a practical limit to the speed of response of such control, and to avoid hunting the arrangement needs to be suitably damped. It will be understood that there are various possibilities similar to the scheme outlined above, such as loading the torque motor against an opposing torque motor, or achieving phase shift by means of a saturating winding. Proper regard must be given in each case to the control means having the desired characteristics.

The thermionic method of control involves the use of radio valves and gas-filled discharge devices. At one time their application was questionable in view of the high factor of safety required, but to-day the standard of performance of such devices has improved enormously, and on the Continent* practical use has been made of this method of control for rectifiers up to 10 000 amperes. It is considered that, provided the valves are given a short preliminary ageing and if two or possibly three are used in parallel, the conditions indicated from the statistical records of the lives of such valves would be amply covered, and the probability of the failure of the control gear is thus practically nil. The thermionic method may well be the most satisfactory where very high speeds of response to fluctuating conditions are required. In addition there is a wide range of choice in the design of the control circuits, from the point of view of both the impulse shape and the voltage regulation. The voltage impulse can be applied to the rectifier grid either by a connection from a resistance in series with the anode or cathode circuit of the valve, or by means of a transformer in the anode circuit thereof.

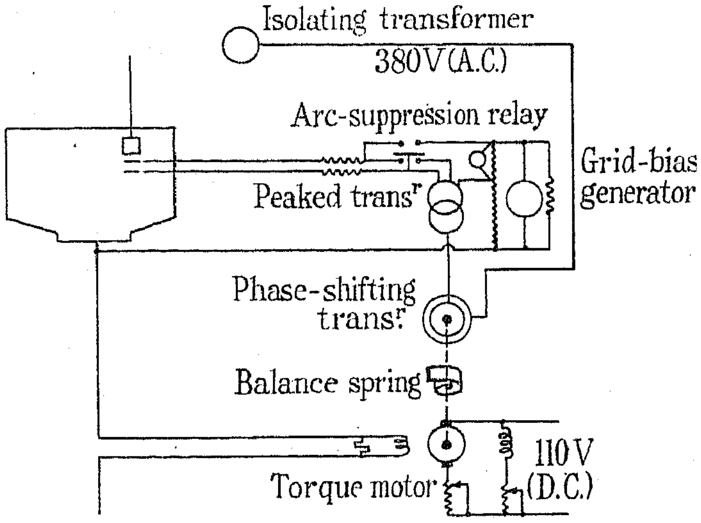


Fig. 10.—Grid-control circuit (shown in simplified form) using peaked transformer and torque motor.

Arc Suppression.

The efficacy with which arc suppression can be carried out depends first upon the nature of the fault, secondly upon the type of load on the d.c. side of the rectifier, thirdly upon the speed with which the negative bias can be applied to the grids, also, if in use, the positive impulses interrupted, and fourthly upon the effectiveness of the grids as screening and de-ionizing devices. In order to energize the grids rapidly, use is made of a high-speed relay, generally of the form of a miniature high-speed contactor. The essential features are a high-speed response combined with non-chattering of the contacts. The time taken for this type of relay to operate is about 2 milliseconds. An alternative method of control, also successful, is to use thermionic devices of the gas-filled relay type, which are almost instantaneous in action.

---

* H. JUNGMICHEL and E. KOTTENHAM: "The Control of Large Rectifiers with Valve Regulators," *Siemens Zeitschrift*, 1937, vol. 17, p. 49. H. ANSCHÜTZ and M. STOEHR: "The Adaptation of Convertors to Motor Control," *A.E.G. Mitteilungen*, No. 6, June, 1937, p. 208.

The suppressing action has been studied with the aid of the cathode-ray oscillograph, and tests have shown that, whilst artificially-induced backfires can easily be suppressed under light-load conditions (see Fig. 11), the suppression with the rectifier on heavy overload is more difficult and requires careful design of the grids and the relay. The whole operation may take 0·02 sec. One reason for the difficulty of dealing with heavy overloads on backfire is the shape of the grid characteristic. This difficulty can be overcome by keeping the anode-current loading low, although it may mean building the rectifier with 12 and sometimes 18 anodes per cylinder. A further point is that in the event of a heavy direct-current feed-back the alternating-current wave with respect to one anode may be completely asymmetrical, in which case recourse to high-speed circuit-breakers is inevitable. Most d.c. circuits, whether they operate rotating machinery or electrolytic plant, or have other rectifiers on a common d.c. busbar, are capable of feeding into a faulty rectifier, and the number of cases in which the high-speed breaker can be dispensed with with impunity are comparatively few. Finally, although the advantage of limiting the fault current is recognized, and arc suppression is becoming a common feature of mercury-arc rectifiers, it may involve a higher arc-drop under normal conditions and a very slight loss of efficiency.

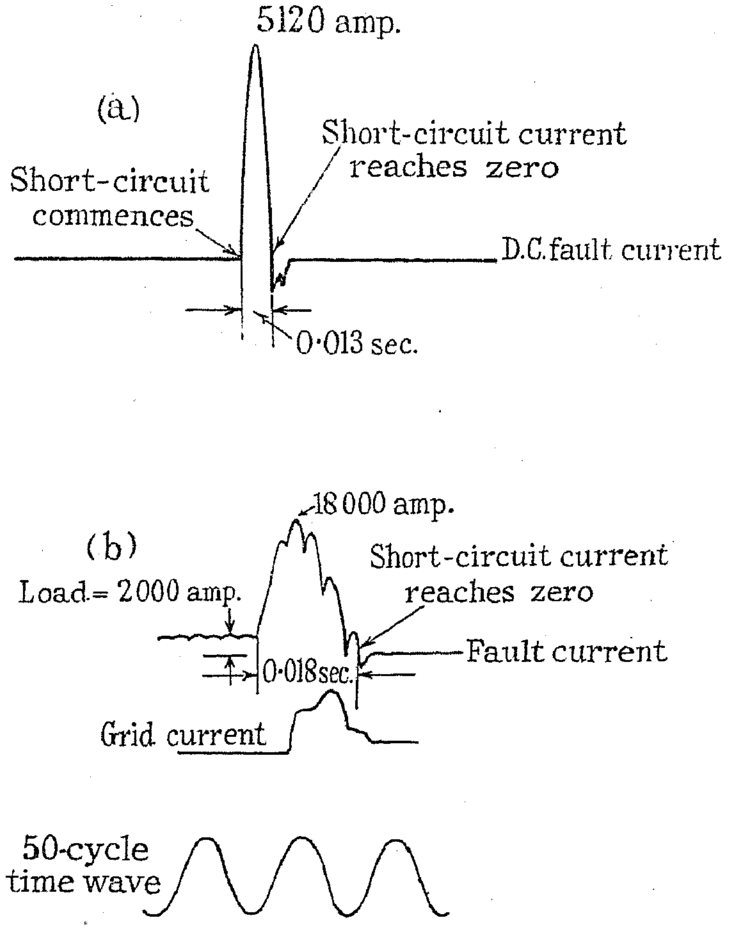


Fig. 11.—Fault-current suppression by control grids.

(*a*) Grid suppression of dead short-circuit on 600-amp. 3 300-volt (d.c.) traction rectifier.

(*b*) Grid suppression of dead short-circuit at full load of 2 000-amp. 600-volt rectifier.

(6) CONSIDERATIONS OF RECTIFIER EQUIPMENT

Throughout the various stages of development the rectifier has had a marked influence on the design and rating of the equipment directly associated with it, and a few passing remarks thereon may be of interest.

On the high-tension side of the rectifier transformer the main switchgear is required to have a higher rupturing capacity than would normally be used for a plant of the same nominal kVA as the rectifier transformer. The factors arising under fault conditions not only combine to increase the duty on the breaker but demand a higher dielectric recovery rate, and in some cases this has resulted in an increase of 50 % on the MVA rating of the switchgear required.

The design of the rectifier transformer is dependent upon several features. On one hand the working conditions demand a robust transformer, but on the other hand the multiplicity of phases on the secondary side, combined with the numerous cross-over connections needed for the maximum utilization of the active material, add considerably to the difficulties of insulation and mechanical bracing. In practice such problems have been overcome, and effective and reliable rectifier transformers can be produced. Various problems still remain, and brief mention will be made of their more outstanding points.

The harmonic problems may be divided into two groups, these being the d.c. voltage ripple and the a.c. harmonics. Up to the present the provision of smoothing gear in the shape of resonant shunt circuits, or alternatively the adoption of a 12-phase system of connections, have proved adequate to meet the case so far as the d.c. side is concerned. (Incidentally a "smoothed" 6-phase circuit has actually less ripple than an unsmoothed 12-phase equipment.) These practices are well established and have already been discussed in many publications. On the a.c. side the position is not quite so well defined. The conditions giving rise to difficulties with a.c. harmonics are well known, but fortunately in practice troubles have been confined to a few isolated cases. At the same time the provision of a.c. smoothing equipment is neither economic nor desirable, and alternative means have to be used to suit each particular case. Numerous theoretical circuits have been devised to produce favourable operating conditions, but in any practical scheme the working of the interphase transformer and the necessity of maintaining correct phase-commutation must always be borne in mind.

The outstanding problems associated with the a.c. side of rectification are:—

(i) Wave-form distortion.
(ii) Resonant effects of a.c. harmonics.
(iii) Interaction of rectifiers whose phases differ in number.
(iv) Interference with communication circuits.

Wave-form distortion has been suggested as a potential source of heating of the alternators in the central station supplying the rectifiers when the total kW of such load becomes very large. As a result of the successful operation of the Berlin City Railways, with their 170 000 kW of plain 6-phase rectifiers, it is realized that in practice the effect is much less than calculation would indicate.

One or two isolated cases of resonance of high-tension lines with rectifier harmonics have occurred, a particular case being that of a 25-mile 100-kV line resonating with the 11th and 13th harmonics. Fortunately such an occurrence is extremely rare and only takes place where the natural frequency of the line is low. It is usually confined to one harmonic. Two solutions of the problem are available. The first is an increase in the number of phases so as to eliminate the resonating harmonic, and in the above-mentioned case it was necessary to proceed to 24 phases to eliminate the 13th harmonic.

The second method is to arrange a phase displacement of the harmonic from one of a pair of rectifiers to cancel out the corresponding harmonics of the second rectifier. This phase-shifting arrangement, whilst requiring an additional transformer, does enable the normal design practice to be followed in connection with the rectifier transformers.

The question of increasing the number of phases to produce a smooth output on the d.c. side, or to eliminate a particular harmonic on the a.c. side, involves the problem of the stability of rectifiers using more than 12 phases. Even with 12 phases there is the possibility of the equipment reverting to 6-phase operation, or the intermittent firing of certain anodes where the a.c. wave is badly distorted by the 5th and 7th harmonics, which, by the way, may arise from transformer saturation independently of any rectifier load. The root of the problem is the small commutating e.m.f. available when the number of phases is large. To overcome this difficulty, circuits giving a steep fall of anode voltage towards the end of the burning period have been proposed, but again this tends to introduce a percentage of 5th harmonic into the voltage wave and its general adoption is hardly likely to meet with favour. The ideal is to provide the maximum of stability for the rectifier with the minimum of disturbance to the system. There is little doubt that for stability the 6-phase connections are ideal, and in view of the general experience they can be accepted as satisfactory. If necessary, however, the position can be made still more safe by the use of alternatively star- and mesh-connected primary windings of rectifier transformers on the same system.

A few cases of interference with communication circuits due to rectifier harmonics are recorded, but with the exception of one or two isolated instances they have not proved serious. Such phenomena are usually due to local conditions, and normally no special precautions beyond the usual smoothing gear are considered necessary.*

The influence of grid control upon rectifier equipment is marked in many directions. In the first place the additional control gear per phase makes it very desirable to limit the number of phases in the rectifier, but on the other hand the smoothing gear requires to be larger to deal with the "sawtooth" wave-form. The overlapping effect of the interphase transformer and its voltage wave-shape in relation to the incoming phase, together with the duration of the positive controlling impulse, needs attention. A more serious aspect of grid control is that of its influence on the power factor; for example, a voltage regulation of 15 % may involve a lag in the power factor down to 0·8 and, should long periods of operation at reduced voltages be contemplated, tap-changing gear is advisable and the grid control relegated to merely smoothly regulating the voltage between one tap-change and the next.

Another aspect of rectifier transformer equipment is the placing of the auxiliaries such as the interphase transformer and the various choke coils. In the case of units of large outputs associated with water-cooled rectifiers, there is usually only the interphase transformer housed with the main transformer in the one tank. With the smaller equipments there are two schools of thought, one favouring the separate disposition of the various components such as the anode chokes, auxiliaries, etc., the other associating the auxiliaries with the main transformer in the one tank. Such practice is conducive to apparent neatness in the substation and the cubicles, but at the expense of the internal simplicity of the transformer.

The problems of temperature control and improvement of light-load efficiency of the air-cooled rectifiers has been further advanced through the more general adoption of fan-speed control chokes, which regulate the amount of cooling and power input to the fans in proportion to the load on the rectifier. The resultant saving compared with constant-speed fan equipment is to a large extent dependent upon the load factor of the rectifier.

In the case of the air-cooled rectifiers, both of the all-metal or the glass construction, in the event of a backfire the rectifier must be isolated with all speed. Anode fuses have been found to give effective protection in this connection; these have undergone a steady change in recent years and are now so designed that they do not fuse under ordinary forward short-circuit conditions, but only in the event of a backfire. Both the chemical-filled and the oil-immersed types are used, but their length is considerably increased so as to render them capable of dealing with any d.c. component in the backfire current. Actually these fuses, made in ratings up to 250 amperes, are a comparatively costly item and their frequent replacement would be most uneconomical. The fact that they so rarely fail is a tribute to the reliability of the modern air-cooled rectifier.

Of the many other items in connection with rectifier equipment, brief mention will be made of the high-speed circuit-breakers only. In these switches, operating times down to 0·012 sec. are used, and it must be admitted that, despite innovations in the way of control grids, fuses, arresters, and the like, the breakers remain the most effective means of protecting the rectifier from

---

* H. Jungmichel: "Harmonics, Ripples, and Interference Voltage of Rectifiers," *Elektrotechnische Zeitschrift*, 1937, vol. 58, p. 417. W. Gerben and H. Kölliker: "H.F. Wireless Interference by Rectifiers," *Bulletin, Schweizerischer Elektrotechnischer Verein*, No. 25, p. 654.

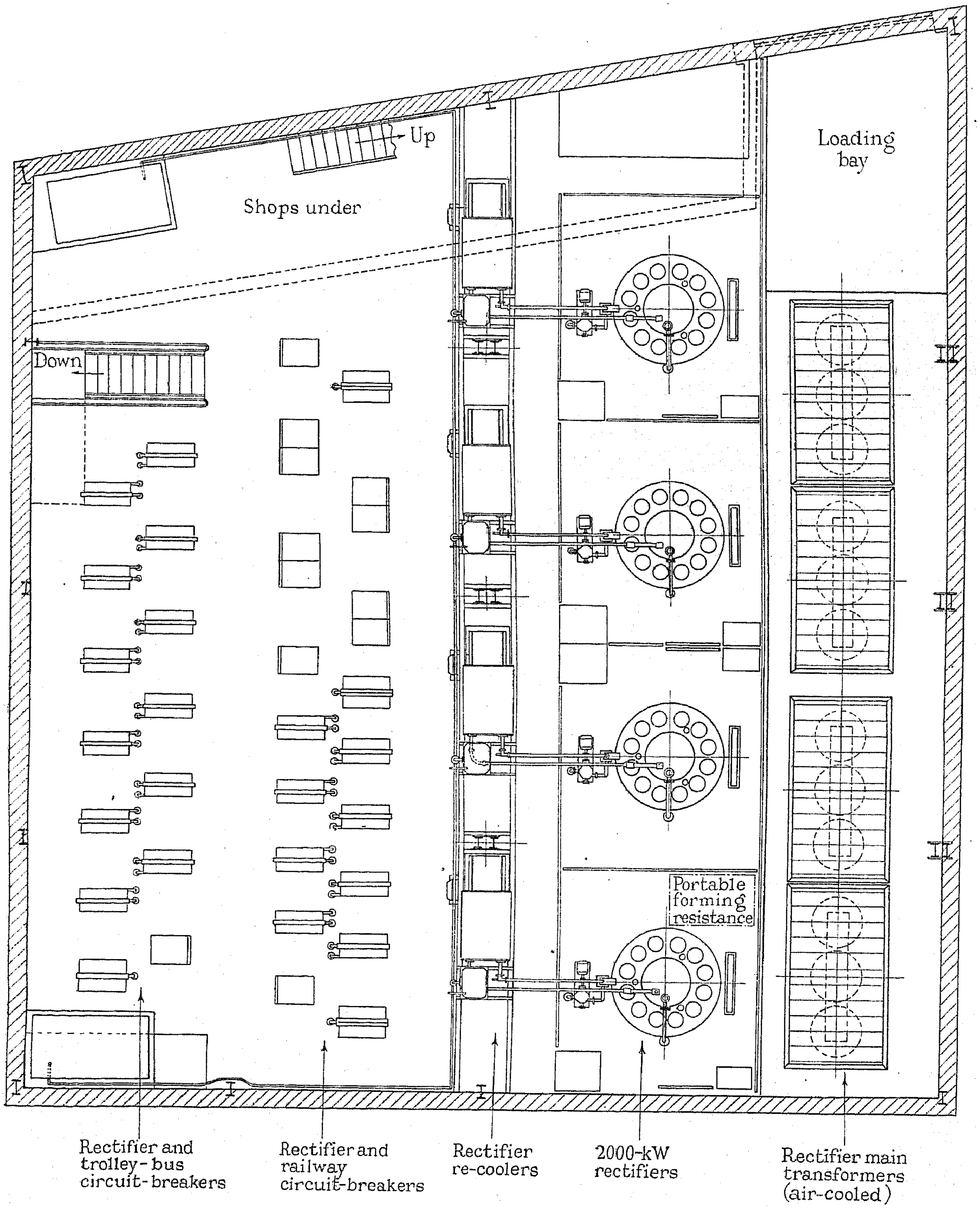

Up
Shops under
Loading bay
Down
Portable forming resistance
Rectifier and trolley-bus circuit-breakers
Rectifier and railway circuit-breakers
Rectifier re-coolers
2000-kW rectifiers
Rectifier main transformers (air-cooled)

Fig. 12A.—Plan of rectifier floor of Camden Town substation.

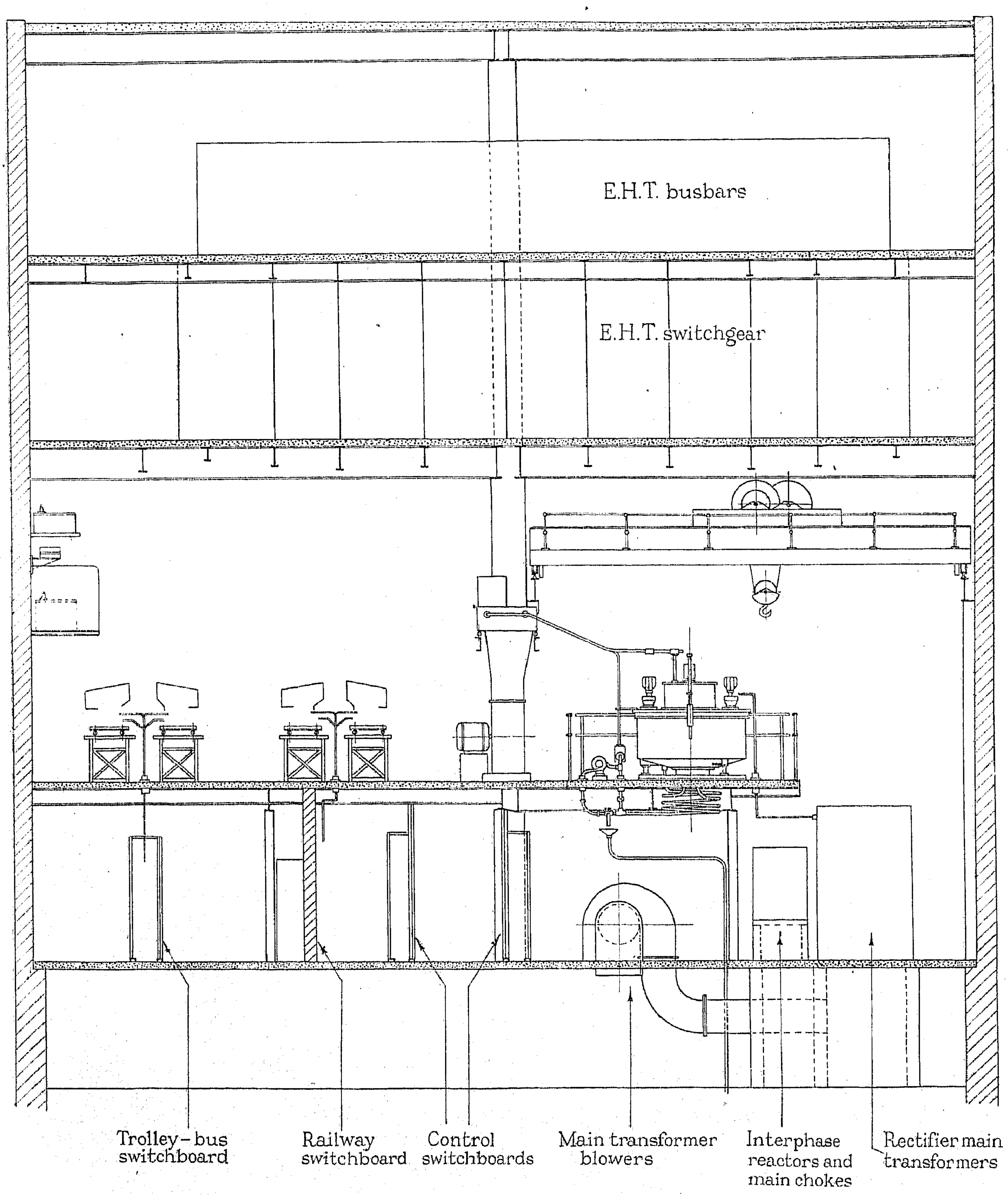


Fig. 12B.—Section through Camden Town substation.

major damage, whether the potential source of trouble be short-circuits, feed-back, surges, or even lightning disturbances on the d.c. track.

Equipment Layout.

The layout of rectifier equipment is rendered very flexible by virtue of the static nature of the plant, both the horizontal and vertical arrangements being possible. In view of the ever-increasing congestion in large cities, and also modern architectural trends, the latter arrangement is becoming increasingly important, and it is not without significance that the largest rectifier substation in this country, the 8 000-kW Camden Town equipment of the London Transport, is of the vertical type shown in Figs. 12A and 12B. The arrangement shows the mounting of the high-tension gear on the upper floor, the four 2 000-kW rectifiers and d.c. high-speed circuit-breakers on the second floor, the control boards and link panels on the ground-level, and the outgoing d.c. cables in the basement. Three of the rectifiers supply power to the electric trains, while the fourth is used for the tramway and trolley-bus system. An interesting feature of the substation is the utilization of the frontage for shop sites.

As a result of the introduction of the pumpless rectifier, compact arrangements are possible even where large powers may be concerned, while heavy cranes and lifting gear may be avoided. It is interesting to consider the possibilities where the three main types of rectifier are competitive, and Fig. 13 shows, by way of example, the layout of equipments for an output of 2 000 kW at 600 volts as supplied by (*a*) glass bulb, (*b*) air-cooled pumpless steel tank, and (*c*) water-cooled rectifiers, respectively. An important factor in any such comparison is the overload rating of the units, and Fig. **13** is based on the heavy traction overloads as indicated. The areas directly occupied by the actual rectifier plants are respectively 0·12 sq. ft. per kW for the glass bulbs and 0·078 sq. ft. per kW for the pumpless rectifiers and also for the water-cooled type. The figures quoted include access space.

(7) THE SCOPE AND PERFORMANCE OF RECTIFIER PLANT

The power rectifier has had widespread application and there are no signs of its limits of usefulness being approached. Both the reliability and economy of rectifier plant are well established, and from the performance standpoint interest lies mainly in the direction of efficiency and overload capacity. Despite the fact that rectifiers can withstand short-circuit without serious damage, their thermal capacity is comparatively low and the duration of the permissible overloading period diminishes very rapidly with increasing overload. The net result often is that where a rectifier plant of capacity adequate to deal with the brief but very heavy overloads is installed, its normal duties so far as the rectifier is concerned may be relatively light. This is particularly noticeable in traction work, and more especially where rectifiers are in use in parallel; in a sense the effect can be interpreted as leading to a very conservative rating of the units for normal conditions, and the fact that it is possible to do this and still maintain a good economic performance is largely due to the flattened form of the rectifier load/efficiency characteristic.

Yet another aspect of the efficiency and overload questions is that of the working voltage for the rectifier. As already mentioned, it is necessary from de-ionization considerations to de-rate the rectifier when the working voltage is raised; on the other hand, the arc drop is approximately the same and a considerable gain in efficiency usually results. The de-rating of the rectifier also reduces the thermal loading, so that if a high-voltage rectifier is designed to withstand momentary heavy overloads it has every prospect of a good performance under standard overload conditions.

Rectifiers for Traction Purposes

It is usual to consider rectifiers for traction work to be divided into two categories, namely heavy traction and light traction. Under the first heading, rectifiers fulfil duties in connection with main-line electrification, regenerative braking, frequency-changing, electric locomotives, and portable substations.

Although two 50/16⅔-cycle frequency-changing rectifier equipments of 3 600 and 4 600 kVA respectively have been installed in Germany, where also rectifier locomotives are being tried out under service conditions, it would appear that such developments will be restricted to the Continent. So far as Great Britain and the Dominions are concerned, most of the traction will be supplied at pressures of 500 volts, or 1 500 volts, or 3 000 volts direct current. Attention will therefore be directed to d.c. traction, and it may be mentioned that the increasing use of the Metadyne and similar methods of motor control are bringing regeneration, with its attendant invertor problems, increasingly to the fore.

Some typical examples of rectifier traction work associated with British industry are the London Transport's system, and the electrification of the Southern Railway, the South African Railways, and the Polish State Railways. A comprehensive survey of the London Transport's electrical equipment has already recently been given before The Institution.[*] It might be mentioned, however, that a unique feature of the undertaking is the employment of each of the main types of mercury-arc rectifier. These range from the 2 000-kW water-cooled types down to the 250-ampere steel pumpless air-cooled rectifiers,[†] and also glass-bulb rectifiers for similar output to the latter. The water-cooled rectifiers are used on the railway services, and the other types on the trolley-bus and tram supplies. Operating conditions are at times severe, ranging from dense traffic in the city to single trains on outlying sections. The fact that an undertaking of this nature with its enormous peak loads is not only largely dependent upon rectifiers, but is relying on them for its extension programmes, says much for the reliability and confidence placed in this type of plant.

The Southern Railway scheme[‡] is noteworthy as representing the beginning of an era long foreshadowed in connection with the British main-line railways. The

---

[*] A. L. Lunn: "Equipment and Performance of Steel-Tank Rectifiers," *Journal I.E.E.*, 1936, vol. 78, p. 123.

[†] "Sealed Metal-clad Mercury-arc Rectifiers," *Electrical Times*, 1936, vol. 81, p. 815.

[‡] *Railway Gazette* (Electric Railway Traction Supplement), June, 1937.

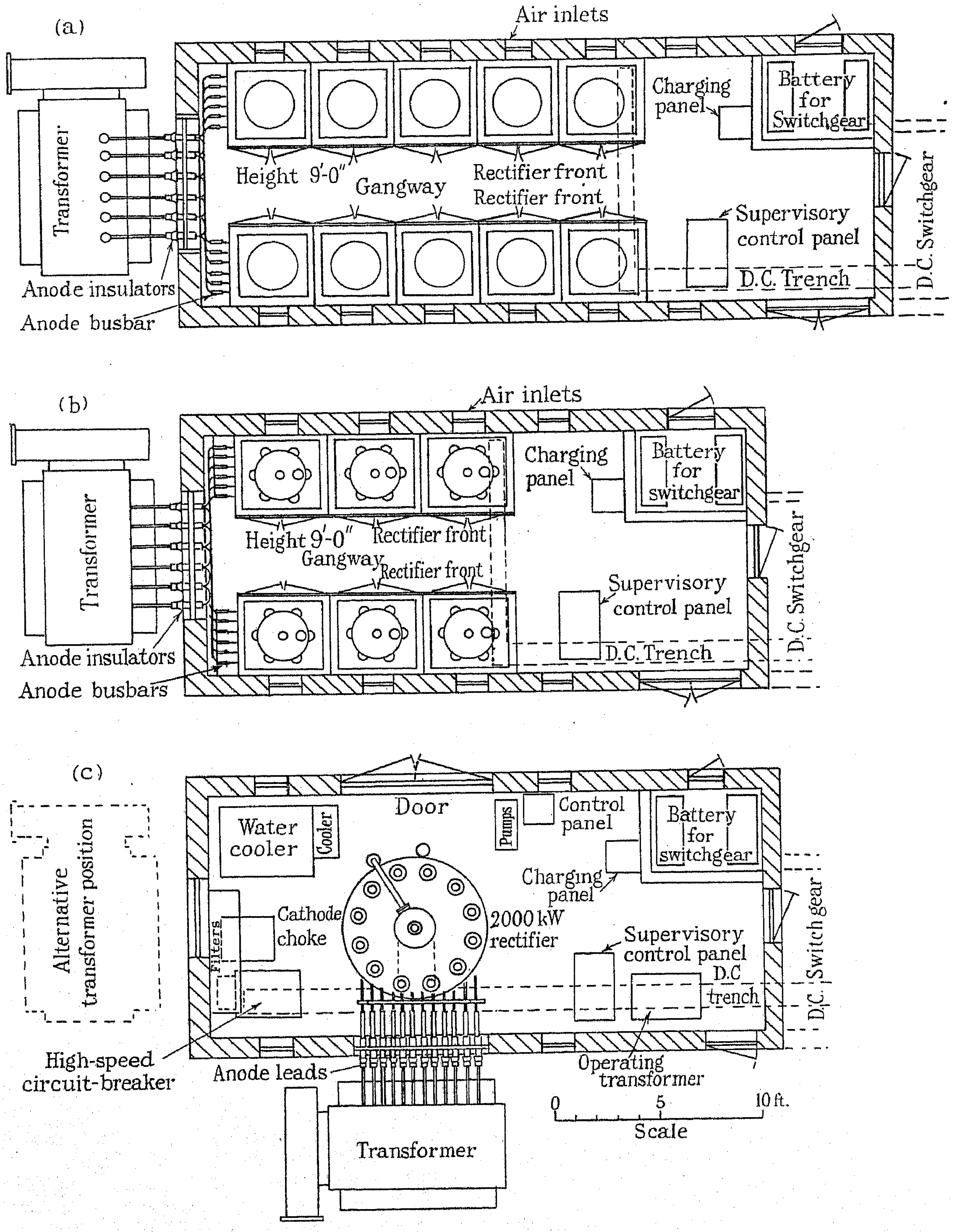


Fig. 13.—Proposed arrangements for 2 000-kW 600-volt traction substation. Overloads: 50 % for 1 hour; 200 % for 15 seconds.

(*a*) Substation with 10 glass-bulb units.
(*b*) Substation with 6 pumpless steel-tank rectifiers.
(*c*) Substation with water-cooled rectifier.

rectifier equipment involved amounts to 250 000 kW, corresponding to 100 2 500-kW equipments. The rectifier equipments are installed in single-unit substations and at certain points of the system operate in parallel with compound rotary-convertor substations. Each equipment consists of a steel-tank rectifier with main transformer and switchgear for operating equipment controlling auxiliary plant, and is designed for the following typical d.c. ratings for traction work:—

2 500 kW continuously at 600 volts,
3 000 kW for 15 minutes,
4 000 kW for 5 minutes,
6 000 kW for 30 seconds,
8 000 kW momentarily.

The South African Railway electrification* represents 320 miles of main-line working at 3 000 volts (d.c.). Regenerative braking necessitated the installation of invertor equipment and, to overcome switching limitations, the use of permanently reverse-connected rectifiers to pass the regenerated current. In common with similar schemes the actual total amount of returned energy to the a.c. system will, after allowing for the portion absorbed amongst the load of other trains, only amount to a small percentage, and even if returned at a low power-factor should not affect the a.c. system. The important feature is that the full retarding force shall be instantly available when required. Special tests with two 1 000-ton trains, and subsequent operating experience, have confirmed this.

Another feature is the use of high-speed relays to suppress the arc by applying a negative voltage to all grids in the case of a backfire or internal short-circuits on the rectifier. Track short-circuits are dealt with by means of external feeder breakers. The forward loads represent a continuous rating of 1 667 kW on each unit, the corresponding overloads being as follows:—

Direct	Inverted	Period
50 %	25 %	2 hours
110 %	100 %	30 minutes
200 %	175 %	1 minute
260 %	200 %	Momentarily

The complete equipment is also rated with a particular load curve. It is interesting to note that in connection with the actual working a loading of almost three times the full load has been carried for 11 minutes.

So far as the grid-control equipment is involved the rectifiers are of normal 3 000-volt construction fitted with double control grids and polyphase excitation. Using the torque-motor-actuated control for the peaky-wave ignition transformer, the response was more than sufficiently rapid for railway service. The use of resonant shunts has effectively reduced the telephone interference factor of the voltage ripple to 0·5 % despite the use of grid control and 6-phase transformer connections. The overall efficiency at full-load rectification was 96 % and at full-load inversion 94 %.

The Polish State Railways† are supplied from thirteen 3 300-volt rectifiers arranged in 6 substations and aggregating some 35 000 kVA. The combined capacity of the power stations supplying the rectifier is 143 000 kVA, and the rectifier load thus amounts to 24·5 %. To meet low ambient temperatures, small heaters are fitted to switchgear control gear. The power transformers are also equipped with a tertiary 6-phase star-connected winding for baking-out the rectifiers at low voltage. The overload figures are 25 % for 15 minutes and 200 % momentarily.

The guaranteed overall efficiencies are:—

Load	5/4	4/4	3/4	2/4	1/4
Efficiency, %	96·07	96·6	96·82	96·72	95·57

The protection on the d.c. side consists of reverse high-speed breakers between cathode and busbars, and forward high-speed breakers between busbars and the track, while, to minimize interference, smoothing reduces the ripple to less than 1½ % of the normal d.c. voltage. Three substations are manually controlled, the remainder being remote-controlled.

Despite the fact that it is a comparative newcomer to the rectifier group, the pumpless steel-tank rectifier has met with considerable success. Some 10 000 kW of this type are already in service. The parallel arrangement of the units for larger powers enables a high efficiency to be maintained, together with overload performances comparable with that of water-cooled rectifiers. Substations of 1 000 kW capacity have been equipped with the new type of rectifier.

A typical example is that of a 600-kW 500-volt equipment supplied to a Glasgow printing works. The two 600-amp. pumpless steel rectifiers are each housed in a cubicle containing the cooling fan and the usual auxiliaries. The d.c. supply is on the 3-wire system, a neutral point for the third wire being efficiently and effectively obtained by means of a rotary balancer. The usual standard overloads and efficiencies were obtained without difficulty.

Yet another example is the 500-kW 600-volt unit supplied for Perth, Australia. This is one of the first grid-controlled pumpless steel-tank rectifiers and is arranged to give constant voltage for all loads up to full load. The control potentials are applied to the grids by the synchronous distributor method, suitable voltage-responsive relays being provided for actuating the brush-rocking gear. The control gear is neatly housed in a separate cubicle from the rectifiers.

Glass-bulb equipment represents a considerable aggregate of installed plant and covers a wide range of outputs, from large 6 500-kW traction substations down to small units for cinema projectors. They are too numerous to be discussed in detail, but the rectifiers associated with the Liverpool, Southport, and Manchester–Bury lines, respectively, might be quoted as typical examples. The former is a 600-volt system with 2 000-amp. rectifier banks, the latter a 1 200-volt scheme with substation capacities of 3 000 amp. In each case the overloads are 25 % for 2 hours, twice full load for 10 minutes, and three times full load for momentary peaks.

Turning to the high-voltage field, a 100-kV experiment in d.c. transmission has been tried out in Switzerland, and a high-voltage d.c. constant-current equipment has been installed at Schenectady, U.S.A.

Mercury-arc rectifiers for radio broadcasting are also well established, amongst the latest achievements being the new Empire broadcasting station at Daventry. The entire main high-tension d.c. supply is furnished by five rectifiers of the steel-tank type rated at 400 kW for either 12 000/14 000 volts or 19 000/22 000 volts. The normal voltage control to these equipments is given by induction regulators, but the rectifiers are also able to give control of the voltage from zero to 22 000 volts by means of grids. A new type of high-speed relay is incorporated to suppress the rectifier arc in the event of flashover in the transmitter valves. These rectifiers have withstood 30 000 volts, 400 kW, for 15 minutes.

---

* *Engineer*, 1936, vol. 162, p. 66.

† *Engineering*, 1936, vol. 141, p. 201.

Mention might be made in passing of the application of rectifiers to film studios, the characteristic type of load being long intervals of light load followed by short periods of heavy load during the actual filming. A typical equipment supplied to the Amalgamated Studios, Ltd., at Elstree consisted of 500-kW 240-volt steel-tank rectifiers. Utilizing the heavy overload capacity in combination with 3-wire working, it will be possible to supply brief lighting loads for 16 000 amp. Special smoothing equipment is provided to ensure the smooth and silent operation of the arc lights.

Two types of rectifier, the pumpless air-cooled steel-tank type and the Ignitron, are being applied to mining work below ground. The former is a 250-kW unit to be supplied to one of the Rand Mines, and the latter is being used in America to give a 225-volt 300-kW supply for haulage and machinery operation. This Ignitron equipment was arranged for full automatic control and voltage compensation for both line and transformer reactance. The compensation was arranged by combining the effects of load and line voltage and applying this to the impulsing transformer neutral. Beyond full load, use was made of the normal shunt characteristic. The overload ratings were 50 % for 2 hours and 200 % for 1 minute. In 6 months' service only one arc-back has been recorded.

All types of mercury-vapour rectifiers are finding application in the chemical industry, large steel-tank water-cooled sets up to 8 000 kW being used. A feature of this class of service is the low-voltage starting required on some of the electrolytic baths, and the possibility of feed-back currents over 10 000 amperes in the event of a rectifier arc-back. As a result both grid control and arc suppression are of importance.

Similar heavy-duty rectifiers are required in connection with rolling-mill work, where in some cases circuits to give the usual Ward–Leonard operating characteristics are used.

Other applications of rectifiers are to electric locomotives, portable substations, high-power tests, hotel loads, printing works, large stores, docks, etc. The foregoing by no means exhausts the applications, but is sufficient to indicate the extremely wide scope possible.

(8) CONCLUSIONS

There is little doubt that the sustained importance of direct-current electrical engineering has been largely due to the progress of the rectifier. This device has enabled the benefits of the flexible control of d.c. plant to be combined with the economics of a.c. distribution. The rectifier has also had a far-reaching influence on transport, and the progress of main-line electrification and trolley-bus systems throughout the world is of significance in this respect.

Rectifiers have now been in course of development for over a third of a century, and whilst there may be comparatively little further change in the essential features there is no reason to suppose that finality in design has been reached. One of the difficulties in rectifier development has been the lack of economical means of carrying out full-load tests at large powers, it is of interest to note that a rectifier-testing station has recently been built at Witton, and is capable of testing rectifiers up to 6 000 kW at voltages up to 4 000 volts, while equivalent tests corresponding to loadings at 12 000 kW are possible.

A study of the rectifiers themselves suggests that air-cooling, even for larger sizes, will eventually be adopted and that the vacuum pumps will inevitably disappear as a unit feature of each rectifier. So far it would be true to say that grid control as a means of voltage regulation has proved less popular than was thought probable a few years ago. Some of the theoretical possibilities have not materialized and there have also been limiting economic factors to other forms of controlled operation.

With high voltages the demand has proved smaller than anticipated; radio broadcasting, rather than d.c. transmission, would appear to be the limit of requirements. So long as the transmitting-valve policy remains as at present there will be little demand for rectifiers above 20 kV. The future of the lower-voltage working is bound up with the question of arc drop, and in this connection the use of single cylinders per anode and also the jet-wave rectifier appear to have brought us to a lower limit than was previously economically possible.

There is little doubt that the great outlet for power rectifiers will remain the 500–3 000-volt range, where not only has confidence in them been established but also their application has resulted in considerable saving to the community as a whole.

ACKNOWLEDGMENTS

The author wishes to acknowledge his indebtedness to the General Electric Co. for permission to publish the paper, and also to the British Thomson-Houston Co., the English Electric Co., the Hewittic Electric Co., Messrs. Bruce Peebles and Co., the Westinghouse Electric International Co., the Hartmann Rectifier Co., and London Transport, for their kind assistance in permitting the use of technical information about their respective rectifier equipments.

[The discussion on this paper will be found on page 456.]

DISCUSSION BEFORE THE INSTITUTION, 17TH MARCH, 1938

Mr. C. E. Fairburn: It appears from the paper that the non-vacuum type of rectifier has arrived rather too late; also that the rotary convertor is now almost obsolete. A number of problems will have to be tackled, however, before the mercury-arc rectifier will be able to supplant the rotary convertor completely.

Dealing first with the glass-bulb rectifier, I am responsible for 33 industrial installations, containing 68 bulbs, for supplying hotels, docks, cranes, etc., and they are almost entirely satisfactory. Where troubles do arise, they are generally due to a failure to realize the service requirements in the first instance. A short time ago we met with various troubles due to unsatisfactory glass, but these have now been cleared up.

Turning to traction installations, the 1 200-volt system of the Manchester–Bury line is run entirely by glass-bulb rectifiers, and has been quite satisfactory throughout the 5 years during which it has been so operated. We also have two glass-bulb substations on the Liverpool–Southport line which have been running for 5½ years, and they too have proved satisfactory. This week we opened the Wirral electrification, which has six substations, all equipped with glass-bulb rectifiers.

With regard to the steel-tank rectifier, we employ a certain number of these for traction purposes, but some of them have not approached the glass-bulb type in respect of reliability. I do not mean to imply by this that the glass-bulb type should always be used for traction purposes; the choice depends on many factors, the first being cost and the second capacity.

There is a great need of a standard specification for rectifiers. Fortunately such a specification is in course of preparation, and I am optimistic enough to think that it may be completed in the near future.

I have used grid control on a few industrial rectifiers for about 4 years, with satisfactory results, but I have still to be persuaded that it is warranted from the commercial point of view, especially on traction units. I think that the fewer complications we have the greater will be the reliability of the equipment. I have recently installed one steel-tank rectifier with grid control for arc-suppression, and so far it has worked satisfactorily, but it has still to prove its value as a commercial proposition. There is no point in having grid control for voltage regulation on traction systems; for arc suppression it may be of some importance, but if there are a number of feeder breakers connected to a rectifier fitted with arc-suppression grids one must be careful to arrange the gear so that every time a short-circuit occurs on a feeder circuit the rectifier itself does not trip out and make all the feeders dead.

Concerning the question of the rupturing capacity of switchgear, if switchgear for a rectifier has to have 50 % greater rupturing capacity than for a rotary convertor, in some instances the convertor will still be preferred, but the need for this increase does not appear to have been established by comprehensive tests.

With regard to the pumpless rectifier, if this had been introduced at the same time as the glass-bulb rectifier it is probable that the latter would never have been developed in the larger sizes because of the apparent fragility of glass, but in practice breakage of glass bulbs rarely occurs, provided the plant is handled reasonably.

With regard to frequency- and phase-changing, I was privileged to see the set which the Germans have put in at Basle, and I was impressed by the low value of interference it caused. One drawback, however, is the large number of small and rather expensive valves required for controlling the set; I was informed that the life of each of these valves was not expected to be more than about 2 000 hours. I was also informed that that was not considered to be quite the best system possible to-day.

(*Communicated*) On page 449 the author states that there are 170 000 kW of rectifier plant on the Berlin City Railways. What percentage is this rectifier load of the total load on the generating system? Very little is known of the effect produced on a power station when the load comes entirely from rectifiers, or indeed when rectifier load forms a high percentage of the total. I should like to know what the effect on the generating plant would be if, say, the rectifier load was 90 % of the total; and, further, I should be glad to know what telephone and wireless interference might be expected under these circumstances from the transmission from the power station to the rectifiers, (*a*) using cable transmission and (*b*) using overhead lines.

I have heard the opinion expressed that if the rectifier load on any particular system exceeds 15 % of the total load, there will be trouble due to the alternators overheating and also due to interference. I should be glad to know whether the author has any experience bearing on these matters, which are closely related to the question whether rectifiers are going to supersede rotary convertors entirely.

Dr. C. C. Garrard: There is still plenty of scope for direct current, not because of the invention of the rectifier, but because the d.c. motor is still the best type of motor for variable speeds. It is no longer necessary to discuss whether the rectifier is preferable to the rotary convertor; that question has been settled, and we have only to decide which is the best type of rectifier and how it can be most advantageously applied.

We must be careful, however, not to expect too much from the rectifier. Comparatively recently, it was said that the rectifier would provide a solution of the problem of long-distance transmission by providing us with a means of transmitting power at high voltages by direct current. In particular, the gas-cooled arc-type rectifier, owing to its special suitability for high voltage, was to be the means to this end. This, however, is a chimera, because technical and financial examination of the question shows very clearly that d.c. transmission cannot compete with 3-phase transmission, however high the voltage may be. For voltages suitable for the d.c. motor, however, i.e. up to 3 000 volts, the rectifier holds the field, and that field is mainly traction.

A question to which some thought has been given recently is whether we can rely entirely on rectifiers for traction systems or whether, as has been held by some engineers, it is better to include a proportion of rotary convertors in the substations. The Berlin city railway system has 170 000 kW of rectifiers, and no other type of converting apparatus at all. The answer to this question seems to be, therefore, that the admixture of other forms of conversion plant is not necessary, and this is so even with regenerative motors on a traction system, as in the case of the South African Railways.

I am inclined to think that for this country, and with multiple-unit stock generally, regenerated current as such is more bother than it is worth. Whether regenerative-type motors be used or not must be determined solely from traction considerations, i.e. considerations of acceleration, braking, and tractive effort. I say this because I agree with Mr. Fairburn's remarks about grid control; the paper shows that its application is very limited.

Other considerations which might limit the complete use of rectifiers on traction systems are the power factor and the odd harmonics on the a.c. side. I do not think that the power-factor question plays a great role, because the rectifier has a power factor of about 0·94 from 25 % load upwards; this means that the generating station will have a slightly lower power-factor, but if the generator is suitably rated no difficulty results. With regard to the odd harmonics in the primary circuit, in 99 % of cases these do not cause trouble if underground cables are used.

I once had an interesting experience of trouble due to odd harmonics on the a.c. side of a 6-phase rectifier installation. The generating station with its step-up transformer and the 33-kV cable had a natural frequency of 550 cycles per sec., and formed a rejector circuit for currents of that frequency. The consequent distortion of the a.c. wave-form was very marked, and steps had to be taken to get rid of it. I mention this point particularly in view of Mr. Fairburn's remarks about a standard specification. If the makers of rectifiers are called upon to guarantee no distortion of the a.c. wave-form due to the presence of these odd harmonics in the primary, they will naturally have to increase the price of rectifiers. In the great majority of cases wave-form distortion will not matter, and therefore I think that that provision should be left out of any standard specification which may be drawn up.

Similar remarks apply, of course, to the d.c. side, though with less force, because the means of eliminating the even harmonics on the d.c. side are very much simpler. Generally these even harmonics on the d.c. side do no harm, and do not interfere with communication circuits. With regard to the alleged necessity of having circuit-breakers of larger breaking-capacity for rectifiers than, for example, for rotary convertors, I believe this to be a myth. I believe it arose from the fact that the original circuit-breakers were not rated with the scientific accuracy with which modern circuit-breakers are rated. If the required rating of the circuit-breaker be calculated in both cases according to the constants of the circuit, a circuit-breaker with that rating can nowadays be used with success.

I should like to refer to the question of the 12-phase transformer. The 12-phase transformer naturally gives a smoother d.c. output than the 6-phase, but it does not eliminate the necessity of smoothing equipment on the d.c. side if an absolutely even d.c. output is required. I think that the 12-phase transformer is a risky thing to introduce. The rectifier-transformer installation even for 6-phase working is complicated enough, and if we accept the added complication of 12-phase, what we gain, if we gain anything at all, will be entirely obliterated by the lesser reliability of the 12-phase transformer.

Mr. E. Gallizia: I have only one criticism of the paper, namely that it makes insufficient reference to the application of mercury-arc rectifiers to large-capacity electrolytic plants, of which, as a rough guess, there must be some 500 000 kW in service.

With regard to the Marx rectifier, 4 years of continuous development work showed the main difficulty to be that of electrode wear, and until this difficulty is removed the chance of such rectifiers becoming competitive with the mercury-arc rectifier for voltages up to 3 500 volts (d.c.) is somewhat remote. With further increase in voltage, as the current for a given kilowatt output is reduced, the problem of electrode wear is simplified, and for very high voltages—up to 300 kV—it would appear that the Marx rectifier is the only practical solution.

Coming now to a comparison of the glass-bulb, pumpless air-cooled steel, and water-cooled rectifiers, biased opinions have led to sweeping statements that one or other is the ideal type of convertor. My opinion is that at the present state of development there is still room for all three types. For very large currents there is still a great deal to be said in favour of the water-cooled unit, whilst at the other end of the range the glass-bulb rectifier has given good results. Between these two limits there is a range which is best served by the pumpless steel rectifier.

In a general way, the pumpless rectifier is undoubtedly the correct line of development, and the range of application will depend on a number of factors such as the range of size of the individual units, loading and climatic conditions, space, and, as Mr. Fairburn points out, capital cost. So far it has only been possible to find two criticisms of the pumpless rectifier: first, that it is heavy and less easy to handle than the glass bulb; and secondly that it is not transparent, so that it is not possible to see what is going on inside the vessel. If these points are to be treated seriously then it can be said that any increase in weight results in the rectifiers being better able to carry abnormal short-period overloads, and the fact that the walls are opaque means that no objectionable light is emitted. It would appear that, in the case of glass-bulb units, steps should be taken to ensure that no light is emitted from the station, in case of attack by aircraft. Furthermore, it is clear that glass bulbs may be damaged even by indirect hits. Great robustness of the pumpless type of rectifier can be achieved provided seals of the type referred to in the paper are used, which, in addition to having high electric strength, show remarkable resistance to mechanical and thermal shock.

The present state of development of the rectifier makes feasible and desirable the preparation of a standard specification, which should include details of the method of carrying out the acceptance tests. Tentative proposals for such a specification have already been published abroad.

A better general understanding of the problem of harmonics and interference with communication circuits would be of benefit. It is not always appreciated that the rectifier designer has very little control over the harmonics in rectifier outputs, as these are mainly determined by the choice of the number of phases. It should also be borne in mind that a demand for a guarantee of freedom from interference in all cases can only result in an increase in cost, which, in view of the small percentage of cases of trouble, is not warranted. Better co-operation between all interested parties would no doubt be an advantage to all.

Mr. T. S. Pick: The paper is disappointing in that it gives no more information regarding the progress of rectifiers of 3 000 amperes with outputs of 2 000 kW than was contained in Mr. Lunn's paper,* published in 1936. Nor does Dr. Thompson's paper mention any marked progress in the problem of regeneration, although regenerative braking by means of Metadyne trains on suburban railways, and for braking on trolley-buses, is now in regular use.

On page 442 the author hints that 3 000 amperes is the largest economic optimum for the water-cooled steel-tank rectifier. The comments I would make on this are: in the first place, this optimum does not appear to show up when the purchase prices of the various types of rectifier are analysed; and secondly, am I to assume that this optimum gives the water-cooled steel-tank rectifier an advantage over all other types as regards efficiency and reliability? In this connection I would ask the author to give more information regarding Figs. 4 and 5. To which point in Fig. 5 does Fig. 4 correspond?

Dealing with the reference to corrosion on page 441, is not the real cure the exclusion of oxygen from the cooling water in the initial design? Has any further experience of oxidation been noted, and, if so, in what type of rectifier?

When dealing with igniter-type units on page 443 the author mentions the use of some grid-controlled mercury-vapour rectifier circuits excited from a synchronous induction generator: could not the individual anodes of the rectifier be timed to strike by a phase-shifting transformer, thus making it possible to dispense with the synchronous mechanism?

Is the Marx-type rectifier any nearer being a commercial proposition than it was when the author gave his previous paper† in 1934? Can he mention the difficulties which are holding it from the market?

In the schedules of work done on rectifier units the one item which is continually occurring is the maintenance, resetting, and renewal of the Pirani gauges; admittedly the insertion of vitreous enamel in the seals has improved matters, but the seals are still a source of weakness in the water-cooled steel-tank type of rectifier.

It is disturbing to learn from page 449 that resonance has been set up on certain distribution systems. The author says that two solutions are available: first, to increase the number of phases; and second, to arrange a phase displacement in pairs of rectifiers. This means that if, after the whole plant has been installed, harmonics become a difficulty, the solution is either rebuilding the rectifiers or rebuilding the transformers; both seem rather expensive expedients, and the first method may not prove satisfactory in operation. This matter of harmonics is very much wrapped up with the problem of inverted working. Has any attempt been made to design the rectifier transformer in two parts, so as to step down from the high distribution-line voltage to an intermediate voltage, perhaps of six or more phases, and then to re-transform this intermediate-voltage supply in rectifier transformers to, say, two or more rectifiers? It would appear that by this method the harmonics could be cancelled out in one part of the transformation circuit, and that some easy form of phase-shifting could be devised to do away with the leading power-factor when the system is working inverted.

Finally, there is the question of regeneration; the bulk of it in this country will deal with the movement of vehicles in large populated areas, and the general requirement will be the acceptance of regenerated current at each substation, in order to avoid dangerous voltages. The installation of a separate rectifier at each point is precluded on economic grounds, nor is the necessary space generally available in built-up areas, so that a true forward and invertible rectifier is urgently required.

Mr. J. C. Read: The author refers to the grid-controlled 3 000-volt rectifiers, for compounding and inversion, which were recently built under the direction of Mr. F. P. Whitaker and installed on the Natal Section of the South African Railways. As that installation is the largest of its kind in the world and is likely to be of importance with a view to future railway electrification schemes, it may be of interest to give some particulars of the operating results. The main connections are shown in Fig. A, from which it may be seen that two rectifier tanks operate normally in parallel as rectifier and invertor respectively, but by means of change-over switches either is made available as a spare for rectifier working. Fig. B shows the arrangement of the scheme as a whole.

Perhaps the most important point that had to be determined by service experience was the degree of reliability obtainable with invertor equipments under severe conditions. Whereas with rectifiers a momentary drop of a.c. supply voltage produces merely a harmless drop of load, with invertors the maintenance of the a.c. voltage is essential to the commutating process at every anode, and failure to commutate results in a short-circuit. This line passes through some of the worst country in the world as regards lightning, and it might therefore be expected that interruptions on the invertors would be more numerous than on the forward-operating equipments. With these conditions in view, the invertor equipments were designed to have the maximum reasonable degree of stability. Experience has shown that lightning and switching surges produce considerably less effect on the invertors than might have been anticipated; the interruptions on the invertors have been negligibly few and not greater than on the rectifiers.

The 88-kV lines feeding the two sections of the system are each about 180 miles long, and this length of transmission line introduced another problem, in that it was essential that the phase of the grid voltage should follow that of the anode voltage instantaneously, in the event of any phase-swinging of the voltage at the end of the long transmission line. Failure to do this would result in large swings of circulating current, and possible hunting

---

* *Journal I.E.E.*, 1936, vol. 78, p. 123.

† *Ibid.*, 1934, vol. 75, p. 603.

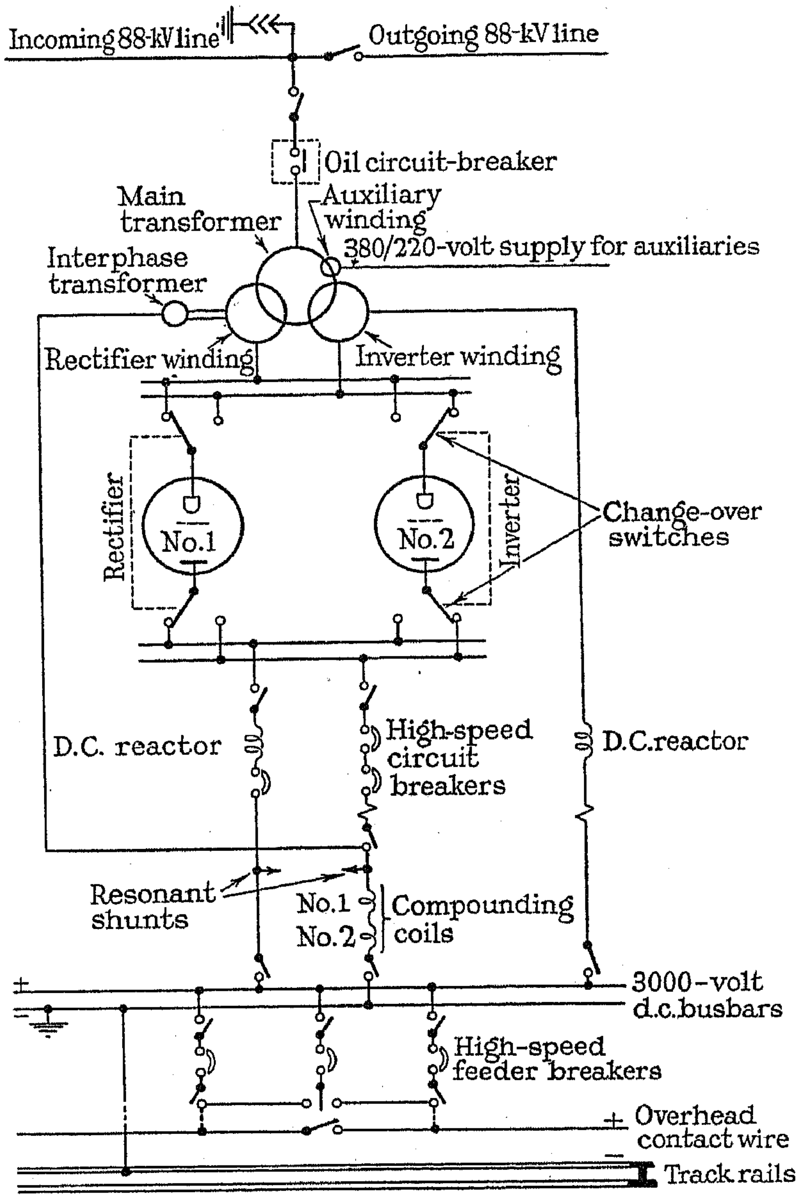


Fig. A

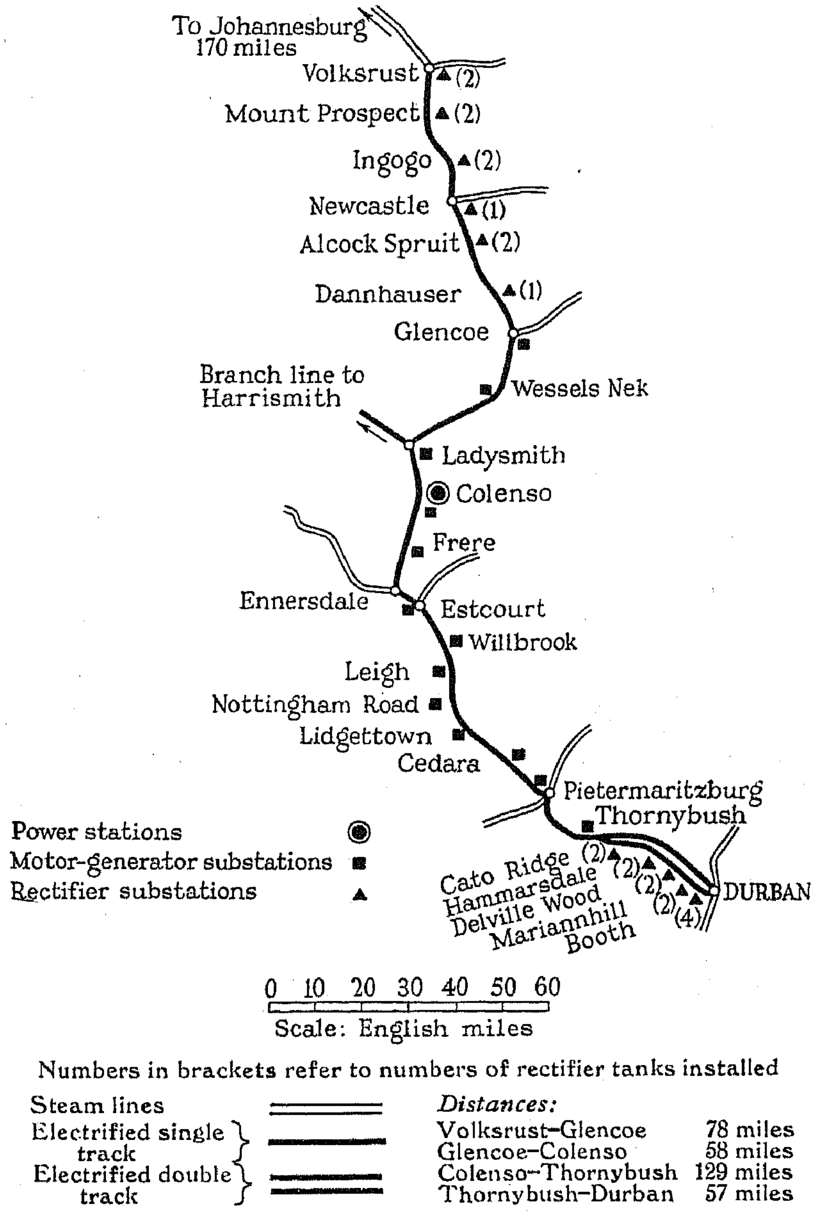


Fig. B

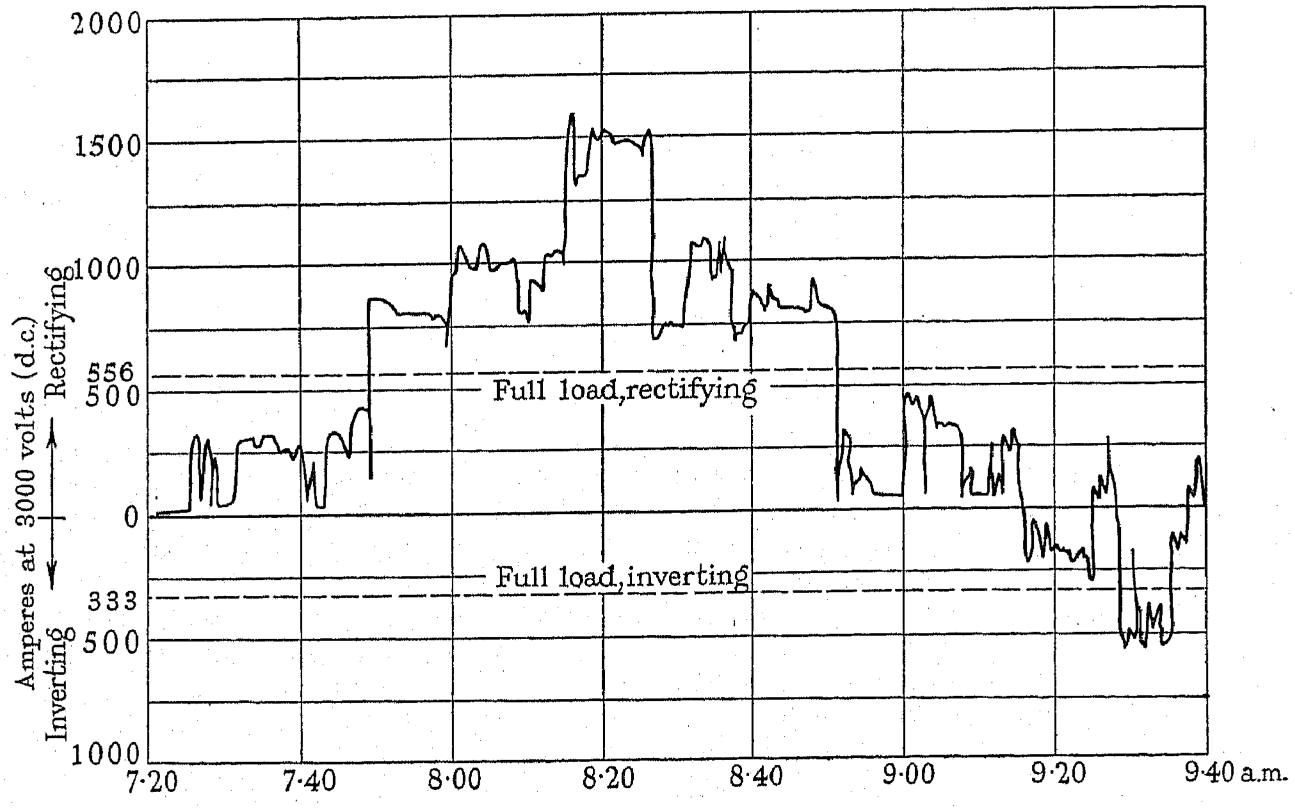


Fig. C

and short-circuiting. The grids were accordingly supplied by peaking transformers, substantially as shown in Fig. 10, as the best method of meeting these requirements. This arrangement has proved very successful. The rectifiers and the invertors work with perfect steadiness with this control, even when tried on a hunting a.c. system, and unbalances or distortions of the a.c. voltage fail to disturb the satisfactory working of the sets.

In order to give the flat compound characteristic required in both directions of operation, it was necessary that the shift of the grid voltage with load should be non-linear, and different according to whether the set was working as rectifier or as invertor. The phase-shift is accomplished by an induction regulator operated by a torque motor, and the special characteristics are obtained by a combination of shunt-field and armature-current control on the torque motor, one of the armature rheostats being operated by the motion of the phase-shifter. The flat compound characteristic in both directions, within the limits of the system stability, is successfully obtained; and the speed of response is ample. The connection shown in Fig. A, which is equivalent in its effect to the equalizer connection used with compounded rotating machines, enables the two flat-compound equipments to work in parallel without any instability of the circulating current.

The Durban section of this system, which carries the heavier loads, has been working fully electric for about 18 months. The Volksrust section has been working for about 6 months (but with a few steam trains still in use owing to shortage of electric locomotives). Very heavy loads have been carried at times; Fig. C is an example of this, and of the easy transition from rectifying to inverting and vice versa. No major troubles have been encountered in the apparatus as supplied; and, while the planning and use of this type of equipment does involve considerably more problems than an ordinary rectifier system, this installation has established the fact that the largest systems can be equipped with substations of this kind with assurance of entirely satisfactory operation.

It does not follow that the cost and complication of such equipments is justified in all cases where regenerative braking is employed; this naturally depends on the cost of energy and on the contour and traffic conditions on the line. In the case of the South African equipments the long gradients and the intervals between trains result in the regenerated energy at the substations being easily large enough to justify the use of invertors.

Mr. A. M. Browne: Fig. 4, giving the arc drop on rectifiers at full load in relation to their size, emphasizes one of the main factors which has helped the development of the glass-bulb rectifier. The curve shows an increase in arc drop from 20 volts for a 500-amp. unit to 25 volts for a 3 000-amp. unit, and 30 volts for a 5 000-amp. unit. Therefore, if a 3 000-amp. equipment is made up with six 500-amp. units instead of one large steel-tank rectifier, a saving of about 15 kW is effected in arc drop: and even if we allow an extra 3 kW in respect of fans or exciters, the overall efficiency will still be 1 % higher with a 6-unit equipment as compared with one large unit. With a 5 000-amp. equipment the difference becomes still greater, and a 10-unit equipment would have an efficiency approximately 2 % greater than that obtained with one large steel-tank rectifier.

Moreover, the multi-unit construction of air-cooled rectifiers increases the overall reliability, as each unit acts as a standby to the others. Furthermore, it has been found that the best way of obtaining an effective increase in anode area is not to increase the size of the anodes but to multiply them. With a steel-tank water-cooled rectifier the number of anodes is accordingly increased to 12, 18, 24, or more according to the capacity of the tank: but whereas a 3 000-amp. equipment would be made with probably 12 anodes, air-cooled bulb-type equipments would have six arms per 500 amp. (approximately), or 36 arms in the case of a 3 000-amp. group. This enormous effective anode area which is obtained with multi-unit banks ensures avoidance of hot-spots and also a small arc-drop.

These advantages of reliability and efficiency might at first appear to be gained at a sacrifice of space, but such is not the case. In this connection the comparison in Fig. 13 of the amounts of space taken by different types of rectifier equipments is misleading, because where space is important the glass-bulb units can be banked in two tiers. With this construction the height is no greater than that of a steel-tank equipment, and the floor area occupied by the glass bulbs is accordingly reduced almost by half of that shown. Experience indicates that with equipments of outputs up to 3 000 kW at 600 volts the steel-tank rectifier has no advantage in regard to space when the auxiliary equipment required to be accommodated with the steel-tank plant is taken into consideration.

The paper suggests that for ordinary capacities on traction circuits and on many power circuits the water-cooled rectifier is becoming obsolete: and this tendency will tend to accelerate, for only on the largest capacities, such as are required for electrolytic and other special process work, can steel-tank equipments show an advantage in the matter of space and cost. All the other advantages, i.e. efficiency, reliability, and freedom from auxiliary gear, lie with air-cooled equipments. This being so, the choice of rectifier plant for most purposes will tend to narrow itself down to the two types of air-cooled mercury-arc rectifiers.

Now, if we follow logically the figures given by the author we must admit that the steel-bulb rectifier can only be developed economically at the sacrifice of certain advantages retained by the glass-bulb equipment. Taking a steel-bulb and a glass-bulb rectifier of the same capacity, it has been found that with a steel bulb it is necessary to make the arc path longer, with the result that the steel bulb has a slightly higher arc-drop for the same capacity. If an equipment of a given capacity is made with a smaller number of steel bulbs than the corresponding number of glass bulbs, then there will be a sacrifice of efficiency in the case of the steel-bulb rectifier because the arc drop in the case of the larger-capacity bulbs will be still greater. There will also be a sacrifice of reliability, because the number of anodes and the number of units in the substation will be accordingly reduced.

It is not correct to say that the glass-bulb unit in its present size represents the highest capacity for which it can be economically or reliably developed, but at the present stage of knowledge of the rectifier there is no technical advantage in increasing the size of the glass-bulb unit, any more than there is in developing a steel-bulb rectifier with a larger capacity than the present glass-bulb capacities. In both cases the development is achieved at the expense of efficiency and reliability without a sufficient compensating economic advantage.

A comparison of the robustness of the two types of air-cooled rectifiers seems at first to favour the steel-bulb rectifier; but in comparing the two types one should take into consideration the weakest link in both, which is the seals. The vitreous-enamel seals used with the steel type of bulb have proved successful, but no more so than the seal used with the glass-bulb type. The latter is made up of a glass with the same coefficient expansion as the lead-in wire, and it therefore forms at once the simplest and the most efficient type of seal imaginable. It can be made as long as desired and is incomparable from an insulation point of view, as, of course, the whole body of the bulb is an insulator.

Reference is made in the paper to the fact that the vitreous-enamel seal can withstand a temperature of 120° C., although in actual service it is never called upon to withstand more than 40–80° C. The seals employed with glass-bulb rectifiers can withstand much higher temperatures than this, and are in fact subjected to temperatures of 400° C. during the manufacturing process. The heat-resisting glass of which the bulbs are generally made does not begin to melt under 1 000° C., whereas the temperatures under which it has to work in normal operation are never greater than about 250° C. What is mainly wanted of the material of which the bulb or container is made is that it shall be able to maintain a vacuum, and for this no better material is available than glass.

Reference has been made by Mr. Fairburn to the rupturing capacity of e.h.t. switchgear controlling rectifier plant; it has been the practice with glass-bulb rectifiers to settle the rupturing capacity of the controlling e.h.t. switchgear according to the e.h.t. system requirements only, and this course has proved satisfactory from both the theoretical and the practical point of view.

The possibility of light emerging from the substation windows where glass-bulb rectifiers are installed was referred to by Mr. Gallizia in relation to air-raid precautions; but many substations have no windows, and where there are windows there is no difficulty in screening them to prevent light showing outside. An interesting point which arises from this is that the transparency of the glass-bulb rectifier enables an inspector to check the correct functioning of any glass-bulb plant visually and in a matter of minutes, whereas an inspection of a plant having opaque bulbs requires measurements and a considerably longer time.

Dr. Garrard has referred to the difficulty of making 12-phase-connected equipments; this has not been borne out in practice with glass-bulb rectifiers. Over 200 000 kW of glass-bulb rectifiers connected in this way have been installed.

Mr. G. Henderson: At the bottom of page 438 the author suggests that the modern tendency is to employ a number of smaller units in parallel rather than a large single unit; is not this remark contradicted by the statement at the end of the paper that many installations have rectifier plants of 2 500 kW?

The author suggests that the steel-tank rectifier has not advanced in size. The number of 600-volt 2 500-kW sets employed in traction work is over 100, but on the Continent there are many sets working at 8 000 amp. on electrolytic work.

The question of the pumpless rectifier interests me because experience on traction work, where the load is very intermittent in many cases, suggests that the vacuum will last for a number of years without the use of the pump. Has the author had any experience of running these steel pumpless sets for long periods (8–10 hours) on ordinary industrial work at full load?

He mentions that rectifiers are reliable in operation at temperatures down to 5° C., but what is said elsewhere in the paper with regard to high-speed circuit-breakers and arc-suppression for steel switchgear rather throws doubt on his statement. I should therefore like the author to expand this point a little.

I cannot see how good overall efficiencies could be obtained in the case of a rectifier working on 500–600 volts, with the arc drops shown in Fig. 4.

Dealing with grid control and arc suppression, I am afraid the author confines his remarks too much to voltage variation, frequency variation, and regenerative control. He seems to suggest that grid control, or the polarized grid, has done nothing to help forward the design of rectifiers. I agree that the external appearance of rectifiers has remained the same, but grid control and regenerative control have had a great influence on the internal design.

The author suggests that the use of grid control means that the equipment must be de-rated, but my own experience is that with proper design one can increase the rating when grid control is incorporated. I should be glad of some further explanation of the oscillograms in Fig. 11. The use of grid control for dealing with short-circuits on the d.c. side is not its most important application: the important application is the rapid prevention of a cut-off when a backfire occurs.

Mr. H. C. Harris: With regard to the pumpless steel-tank rectifier, I should like to ask the author whether special alloy steel is used to obtain airtightness, and also whether the thickness of the tank of this type of rectifier has to be increased beyond that of ordinary tank rectifiers. Also, is the direction of the grain of the steel important, and should it be at right angles to the pressure of the atmosphere? I should like to know what tests are made for airtightness in the case of the pumpless rectifier, before it is put into service.

When repairs are necessary to the steel-tank rectifier a considerable amount of time has to be spent in taking the plant to pieces and afterwards baking it out. In the case of the glass-bulb rectifier, on the other hand, all that is necessary is to get a spare bulb from the makers.

Finally, I should be interested to learn something of the comparative costs of the three types of mercury-arc rectifier. At what size does the water-cooled steel-tank rectifier become cheaper than either of the other types?

Mr. J. North: Regarding Mr. Browne's suggestion for installing glass-bulb rectifiers in double tiers, one objection to this is that it would make the sets so high that it would be necessary to have some kind of light crane to lift the valves into position, and, generally, access would be rather difficult. I would rather suggest that larger units should be used. Taking our own standard sizes of bulbs; which will carry an overload of 50 % for 1 hour, 6 units would occupy a floor space slightly less than that taken by the pumpless type of rectifier for an equal total capacity.

With regard to the high-voltage glass-bulb rectifier referred to on page 439, I should like to know why the author mentioned 9 anode arms. I suppose there is some phenomenon which necessitates a change in the number of arms, but I have had no experience of the larger number of arms, for general purposes. I have, however, had experience of high-voltage rectifiers for use on wireless transmitting gear working at 15 000 volts and 50 amperes, with grid control, and no difficulty was encountered in connection with the 6-arm valves employed.

I should also like to know why the author says that the anode has a short life owing to corrosion of the electrodes. Does he not use a graphite anode, as we do?

Mr. B. Wood (*communicated*): Doubt has been cast in the discussion on the fairly general belief that mercury-arc rectifiers are liable to stress the a.c. breakers more highly than do rotary convertors of equal rating. It has been suggested that this impression is due to the breakers not having been capable of their rated duty. This is no doubt true in many cases, but is irrelevant since the breakers which behaved satisfactorily on rotary convertors were presumably equally over-rated. There is ample experience of very considerable over-voltages being impressed on the a.c. and d.c. sides, owing to rectifiers backfiring.

A few years ago, two large rectifiers when first installed gave rise to a number of backfires which definitely overstressed the oil circuit-breakers. These were of a size which was considered adequate on the basis of experience of rotary convertors. They were afterwards replaced by larger breakers of the same type. At the same time a Continental tested breaker of much smaller physical dimensions was connected in series and set for instantaneous tripping. This certainly cleared the faults, but at the expense of causing flashovers outside the breaker. In one case a flashover took place over a distance of 24 in., which, on a 6·6-kV system, seemed to imply a formidable over-voltage. At the time no rational explanation could be given.

A theory which fits the facts has since been offered, as follows: The clearance of a backfiring rectifier from the d.c. and a.c. supplies by the respective breakers does not immediately cause the arc to go out. A local circuit remains in which a current can circulate, as shown in Fig. D. The inductance of the transformer circuit causes the firing anode to continue to discharge into the backfiring anode for some time. The decrement is determined by the time-constant of the local circuit, which may be very high in a large unit with an interphase transformer. The current finally falls to a value insufficient to maintain the arc, whereupon an unstable point is reached and the arc suddenly snaps out. The very rapid fall of current induces a high e.m.f. in the transformer winding, in view of its high inductance. An e.m.f. corresponding to the turn radio is induced in the primary winding on the same limb. If this takes place just after the breaker has interrupted the a.c. arc, the induced impulsive voltage may break down the gap and the rupturing duty may be materially increased. If it is so long delayed that the breaker has already opened, a flashover may take place from any open connections, or, in high-voltage rectifiers, the anode or other cables may be punctured.

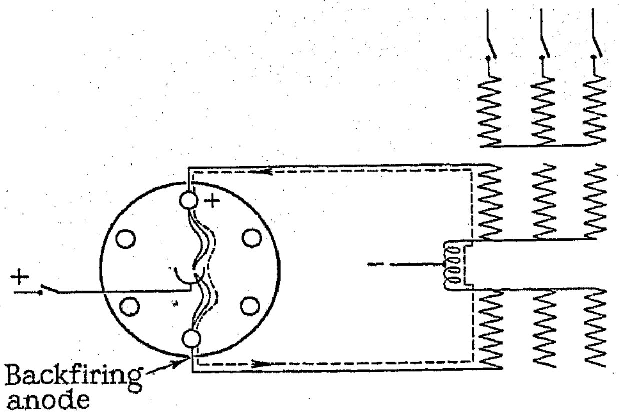


Fig. D

One remedy appears to be to connect sufficient capacitance on the transformer primary side, e.g. by the use of sheathed cables and ironclad switchgear. The employment of a delta connection for the transformer primary may assist by providing a path, albeit one of high impedance, for the surge discharge. Surge arresters connected across the transformer terminals should also be of use, provided they are of the modern type with very short time-lag, and not of the conventional horn-gap design, which appears to be quite ineffectual.

[The author's reply to this discussion will be found on page 468.]

NORTH-EASTERN CENTRE, AT NEWCASTLE, 28TH MARCH, 1938

Mr. J. C. Read: The last three years have been noteworthy for the placing of several large contracts for railway substation equipments. These contracts, which have been open to international competition and have been mainly for 3 000-volt equipments, have included the electrification of the Durban to Volksrust section of the South African Railways (36 000 kW); the Warsaw suburban system of the Polish State Railways (29 000 kW); the Central Railways of Brazil (15 000 kW initial, 35 000 kW ultimate); the Johannesburg suburban system (33 000 kW); and a number of smaller contracts. About 90 % of this business was secured, in the face of world-wide competition, by British makers. These large 3 000-volt installations are now all installed and are giving good service.

With regard to the water-cooling of rectifiers, I think the author is altogether too pessimistic in his reference to the dangers of pinholes. We do not employ protective coatings such as might encourage pinhole corrosion, and we have never had a pinhole, or any other appreciable corrosion, in a water jacket, either in the works or in service. I think it is perfectly feasible to provide rectifiers with trouble-free water-cooling systems.

It is frequently stated that rectifiers equipped with arc suppression are superior to rectifiers not so equipped. I do not think this is correct; arc suppression has its value for reducing the shock on the a.c. system and for lowering the maintenance costs on circuit-breakers, etc.; but, so far as rectifiers are concerned, I believe that for a given size and rating a rectifier without arc suppression has a performance equal to or better than that of one so equipped. The Continental tendency appears to be to equip rectifiers with arc suppression so as to render backfires innocuous when they occur; the tendency here is rather towards keeping the plant as simple as possible and directing endeavours to making the number of backfires negligible. This policy is meeting with some success, as indicated by the fact that at present we can instance complete contracts where large numbers of sets of the highest voltages and most extreme ratings have been in normal service for a year or more and where there has not been a single backfire.

I think this tendency to simplification might well be pushed further in the case of the water-cooled rectifier. Many of the auxiliary devices often fitted on these rectifiers can, with suitable design, be eliminated. Examples are the various thermostatic and other valves in the water circuit, all of which are easily avoidable; the vacuum relay (and the Pirani gauge, which, without the relay, has no justification), which either " locks the stable door after the horse has gone " by waiting for the vacuum to be impaired before it starts the vacuum pump, or trips the plant off load at a vacuum limit that has no connection whatever with whether a backfire would have occurred; the fore-vacuum relay, which controls a vacuum pump that is more simply and reliably controllable in other ways; and the barometric seal and various thermostats, which seek to provide against faults that should be corrected at the source. With proper design all these devices, which unnecessarily complicate the water-cooled rectifier, can be omitted without sacrifice of reliability.

Mr. E. Gallizia: It has been stated that a metal rectifier is less efficient than a glass-bulb rectifier owing to losses taking place in the conducting walls. There seems to be no theoretical justification for such a statement, and experiments have shown it to be unfounded.

With regard to glass-bulb rectifiers, Mr. Brown pointed out in the London discussion that, as the size of the bulb is increased, the losses also increase owing to the necessity of increasing the length of the arc path, and that therefore, apart from other considerations, the limit of size appears to be about 500 amperes. In this connection it should be pointed out that the arc drop is not entirely dependent upon the length but also depends on the cross-sectional area of the arc path, so that in a steel unit, owing to the much greater latitude in determining the proportions without introducing any mechanical weakness, the arc drop can be maintained well within economical limits.

Liquid-cooled pumpless rectifiers can be made, but owing to the simplicity of air-cooling over liquid-cooling, air-cooling should be exploited to the utmost.

Future developments in mercury-arc rectifiers may result in further reduction of the arc drop; but this is not of such great importance for the higher traction voltages, as a 3 000-volt rectifier cylinder already has an efficiency of 99 %.

There are a number of water-cooled steel-tank rectifiers in this district, and it would be interesting to hear of the results obtained with them.

Mr. G. Lintott: The section of the paper dealing with experimental types is of particular interest, and it would appear that in the course of a year or so the mercury-arc rectifier may have a serious competitor in one or other of the non-vacuum types.

The author has been very frank and fair in his treatment of grid control, and his remarks should enable us to view the grid-controlled rectifier in its right perspective in relation to uncontrolled rectifiers and other converting plant. Considering one use of grid control, namely that of d.c. voltage regulation, the a.c. line volt-amperes input is constant for a given d.c. output (neglecting secondary effects), while the d.c. voltage may be varied by altering the angle of ignition. It follows that the supply power-factor is directly proportional to the d.c. voltage, and hence to the cosine of the ignition angle. If secondary effects, such as overlap, etc., are considered, lower values of power factor result. It seems to me, therefore, that where a voltage regulation of 10 % or more is required the uncontrolled rectifier with tap-changing on supply transformer will, from the standpoint of supply power-factor, be superior to the grid-control method of voltage regulation.

In connection with the question of arc suppression, dealt with on page 448 and in the oscillogram (Fig. 11), the author states that the shape of the grid characteristic is one reason for the difficulty in dealing with heavy overloads on backfire. I am not clear why that should be. I should like him to enlighten me on this point and also explain why the grid-current curve in the oscillogram has the shape shown.

I should also welcome the author's opinion on a difficulty I have experienced in measuring anode input to a 6-anode 5-kW 260-volt glass-bulb rectifier. This rectifier is fitted with grids, though these were not in use in the test described below. The transformer was in delta-double-star, with interphase transformer. Wattmeters indicated steady primary input, the d.c. voltage and current output was steady, but the anode input showed a slow pulsation. This was measured by a wattmeter with its current element in the lead to the anode and its pressure element between the mid-terminal of the interphase transformer and the anode. I do not know whether this anode-power pulsation is peculiar to the rectifier described, or whether it is characteristic of all 6-anode rectifiers operating double 3-phase. If the latter is the case I should like the author to suggest reasons for it. An interesting point in connection with this is that the use of current transformers for measuring anode currents and anode input-power is the source of very large errors; they should not be used. I am wondering what is the right kind of instrument to use for such measurements.

The paper deals with the progress made in power rectifiers. One is tempted at times to think that the power rectifier is following the same route as the radio valve, where the diode was succeeded by triode, tetrode, etc., and has, I think, now arrived at the octode stage. From Fig. 10 it appears as if we have reached the tetrode stage in the power rectifier. I should like the author's assurance that there will be no further increase in the number of grids. Presumably, if in naming the rectifier we adopted the same procedure as that used for the radio valve, we should call the uncontrolled 6-anode rectifier a heptode.

Mr. R. J. H. Beaty: I should like to ask the author what current the air-blast type of rectifier is capable of dealing with continuously at 100 kV (d.c.).

Mr. W. A. A. Burgess: I am interested in the statement at the bottom of page 437 regarding the low cost of rectifiers, and I should like to know what cost per kW the author considers to be low.

With regard to pumpless metal-cased rectifiers, are the containers of metal only or are they covered with some material to render them vacuum-tight?

Can the author give us any idea what percentage of the output voltage should be applied on the grid to prevent the arc from striking prematurely when using grid control?

Mr. W. A. Royle: Mr. Gallizia has asked whether anyone would give their experience with steel-tank rectifiers. The Sunderland Corporation, in December, 1935, installed two 1 500-kW steel-tank rectifiers converting from 5 000-volt 50-cycle 3-phase current to 550-volt direct current. These rectifiers have now been in continuous operation for $2\frac{1}{4}$ years. The guaranteed efficiency was 93–94 % according to the load, and on test these efficiencies were all improved upon.

Under actual running conditions covering 18 hours per day (for a proportion of which time the rectifiers are operating on a very light load) the average efficiency is $93\frac{1}{2}$ %. The rectifiers are not fitted with grid control, and, apart from the ordinary attendance given by the substation attendant in cleaning and seeing that the relay contacts, etc., are in working order, and also that the high-speed circuit-breaker contacts are clean and the cooling-water system is topped up, no repairs of any kind have been necessary and we can fairly state that during their $2\frac{1}{4}$ years in commission there has been no expenditure on repairs. The makers advised lifting the tank from the water jacket once a year in order to inspect the conditions. This has not been done; and as there is no indication of increased heating on the tank case and treated distilled water is only used in the closed cooling circuit, I do not propose to lift the tank as I feel that it can safely be left for several years.

Each rectifier is fitted with a tuned filter circuit, and there has been no complaint of interference with wireless. Also, there has not been a single interruption in the supply since the rectifiers were put into commission.

Under normal conditions the rectifiers run on approximately $\frac{1}{2}$–$\frac{3}{4}$ load, but on Bank Holidays when there is heavy traffic to the seaside, and on football Saturdays, the rectifiers have carried up to 25 % overload without showing any signs of overloading, and the attendants are only made aware of the overload by the meter and demand-indicator readings.

The main rectifiers would appear to be absolutely reliable and require no attention, and my only comment is that it would be better if such a reliable piece of plant did not have attached to it so many protective relays, including the automatic gear for switching on and off the cooling fans and vacuum pump.

From the reliability of the sealing, the backing-vacuum pump appears to be an unnecessary auxiliary. This pump is controlled by a time switch and operates for 5 minutes four times per day, but there is no indication that it is actually required to maintain the vacuum.

[The author's reply to this discussion will be found on page 468.]

SOUTH MIDLAND CENTRE, AT BIRMINGHAM, 4TH APRIL, 1938

Mr. J. A. C. King: Some time ago I saw a comparatively small rectifier which had a very interesting and simple ignition system. It consisted essentially of a side tube which had its orifice near the surface of the mercury pool but just below it. There was a thin neck of mercury between the main pool and this side tube. The ignition method consisted in sending a heavy current from the mercury in this side tube to the main pool. The comparatively small thread of mercury over the glass ridge between these two larger bodies vaporized and caused a hot spot, and the main anodes took up duty. I should like to ask the author whether this method is practicable or has been used for the larger units.

Mr. J. W. Gibson: The possible advantages of d.c. transmission, using rectifier equipment, are well known. Will the author therefore summarize the disadvantages which lead him to think that there is no future for such a system?

Why is it necessary to use auxiliary valves for the ignition of Ignitrons? Are these valves used simply for controlling the number of half-cycles of a weld, or are they still necessary if the rectifier is to run continuously?

Both of the author's oscillograms of fault suppression by grid control (Fig. 11) show a small reverse current before final extinction. What is the cause of this?

Mr. W. F. Baker: There are two questions I should like to ask.

First, I should be interested to know what is the most important condition of distress which determines the overload capacity for the various types of rectifier.

Secondly, with regard to the pumpless air-cooled steel-tank rectifier, one great advantage of this appears to be its suitability for operating in countries where extremely low temperatures are experienced. Further, the possibility of preheating the air blast (which could be done very quickly) should facilitate starting and reduce the chance of backfiring. In tropical countries, on the other hand, it would be interesting to know whether, by cooling the air blast, any substantial increase in full-load rating can be secured. Temperature control of the air blast seems to offer much scope for investigation, and I should be glad to know what has been done in this direction.

Mr. A. N. D. Kerr: I should like to ask the author for more information regarding d.c. voltage ripple. It is well known that voltage ripples can cause difficulty on d.c machines, and in many installations these ripples are the cause of rapid brush wear. This question of voltage ripple was brought home to me forcibly when a small motor, of about $\frac{1}{6}$ h.p. at 1 400 r.p.m., was supplied to drive a compressor running at 250 r.p.m., which is a very low speed for a compressor; and although the motor was well within its loading, as shown by ammeter readings, brush wear was excessive. An oscillograph record was taken, and revealed that the brushes were carrying more current than the main current shown by the ammeter, owing to the pulsating load from the low-speed compressor. I should like to know to what extent rectifiers are responsible for brush wear in d.c. machines.

Mr. A. Manighetti: The author mentions the necessity for switches of a higher rupturing capacity for the control of the high-voltage side of rectifier transformers than would be normally used for other types of plant of the same nominal kVA capacity. We know that this is due to the magnetization of the transformer core by the heavy d.c. component resulting from a backfire. The author states that in some cases this has resulted in an increase of as much as 50 % in the MVA rating of the switchgear; that is to say, where normally we could use a switch rated at 150 MVA we should have to increase the rating to 250 mVA. In my opinion this is a great disadvantage, and I should have thought it possible to find means for reducing the effects of a backfire. Could the author give us some means of arriving at the switch rating?

My second point is in connection with errors in metering on the d.c. side of rectifiers due to the ripple, and in current transformers, instruments, etc., on the a.c. side due to the harmonics. In the case of power-factor measurements in rectifier circuits we have to consider a distortion factor as well as the displacement factor ($\cos \phi$); what is the extent of the error in an indicating power-factor meter? It appears to me that with the increased use of rectifiers in railway electrification the rectifier plant on a system may well form a large percentage of the total load, in which case errors in metering may become serious.

Lastly, I should be glad if we could be given some idea of the cost per kilowatt of the various types of rectifiers.

Mr. E. Gallizia: It is rather surprising that, although for 30 years there have been available steel-tank rectifiers with vacuum pumps and glass-bulb rectifiers without such pumps, only within the last 3–4 years has there been available a pumpless steel rectifier. It has not been a case of not appreciating the advantages of such a rectifier; early investigators discovered difficulties due to porous material and bad welding and, of course, there was not available a perfectly vacuum-tight seal which was at the same time highly insulating and very strong mechanically. Another reason for the delay in the development of the pumpless rectifier was that the invention by Dr. Gaede of the mercury-vapour diffusion pump, with its great increase in pumping speeds, led investigators to take the path of least resistance and fit all steel rectifiers with pumps.

Referring to the arrangements for a 2 000-kW substation shown in Fig. 13, the present stage of development of the pumpless rectifier shows that it is possible to deal with 500 kW in one cylinder.

There is a tendency on the Continent to specify lower overloads for glass-bulb equipments than for steel-tank rectifiers, on the basis that the inherent overload of glass bulbs is much smaller. On this basis the pumpless steel rectifier should have further intermediate overloads. Bearing in mind, however, that the buyer is more interested in the result than in the inherent characteristics of the individual units, there seems little point in doing this, particularly as it is only fair to compare performance on the same basis of overload. Thus, a standard specification should call for the overloads which are dictated by the type of service, such as industrial, light traction, and heavy traction, and not by the type of plant.

Mr. J. H. Patterson: One of the great disadvantages of early rectifier plants was their instability, shown by frequent backfires. The phenomenon to which I refer was one in which an anode developed a hot-spot and started to emit an electronic stream, thus converting itself to a cathode into which the other phases fed, causing a dead short-circuit across the secondary side of the main transformer. I am of the opinion that no circuit-breaker yet constructed, either h.t. or l.t., could operate with sufficient speed to clear such a fault without involving other rectifiers running in parallel. I should be glad to know what improvements have been made to obviate this trouble.

As regards the pumpless type of rectifier, in the old days trouble was experienced in obtaining a reasonable vacuum, and after a flashover a pump was of considerable use when the work of re-forming the anodes was in progress. I should like to know whether, should such a flashover take place on a modern pumpless rectifier, the anodes have to be re-formed; and, if so, what method of procedure is adopted.

The advantage of the glass-bulb rectifier over its steel-cylinder prototype is that, should trouble occur in one cubicle, it is possible for other rectifiers running in parallel to maintain supply while the damage is being dealt with; whereas, with the steel-cylinder type, a large-capacity unit is put out of operation. A disadvantage of glass-bulb rectifiers is that they require extremely careful handling, and it is my experience that after such a rectifier has been on load for some time it is far more likely to sustain damage in transit than would be the case if the bulb were new.

As regards grid control, I would emphasize that this was in the first place designed to give fine d.c. voltage control such as would be possible by using an induction regulator, a far more costly piece of apparatus.

The author mentions that it is desirable to install a special type of fuse to serve as protection in rectifier circuits. I think this is of paramount importance and that a fuse of high rupturing capacity should always be employed, otherwise under fault conditions the inductance in the circuit will cause the voltage to rise to phenomenal values and do far more damage than would have occurred if the original conditions had been adequately cleared by a proper fuse. The ordinary type of cartridge fuse with bare tinned-copper element is of no use for such conditions as these.

The copper-oxide film rectifier, which is at present coming into great favour, has the advantage that it is robust, of simple construction, and has none of the inherent faults of other rectifiers. The only limit to its output is set by temperature-rise, and should any portion of the rectifier fail to function it is possible by means of suitable relays to disconnect it from the circuit before any material damage is done. The copper-oxide film rectifier has an indefinitely long life, but its first cost is rather higher than that of the steel-cylinder and glass-bulb types. It is very flexible: large numbers are in use for plating purposes at low voltage, and units have also been designed and are in use for X-ray purposes, necessitating a d.c. voltage output of 400 000 volts.

Mr. H. H. Taylour: The author gives the impression that some inherent defect of grid control has hindered its more universal adoption. The power-factor problem is admittedly a serious one in some instances, but the reason for the somewhat limited application of grid control is not so much that it does not perform up to expectations as that the services it can render are not required very often. We can take it that the various ingenious frequency-changers described in technical articles of (mainly) Continental origin do perform satisfactorily, but we have no need for them in this country. The voltage regulation, regeneration, and arc suppression provided by grid control are all quite satisfactory, but they should always be investigated with due care in individual instances. The real advantage of grid control is its potential rapidity of operation, particularly where fluctuations have to be corrected in the shortest possible time. It may be advisable to follow it up with an induction regulator or tap-changer to improve the power factor, but these devices are notoriously slow in operation.

Both Dr. Garrard and the author are rather pessimistic about e.h.t. direct-current transmission, and as things are at present I am inclined to agree with them. Should the use of cables as opposed to overhead lines become more general for primary transmission, and as the capacity of generating plant in a grid system increases, the advantages of the d.c. link for the shorter distances will be realized. The high capital expenditure in the face of a relatively low financial return which has to be faced is likely to delay its adoption, at any rate for some years.

With regard to troubles due to harmonic interference, I should like to join with Dr. Garrard in suggesting that each case should be investigated on its own merits. The number of cases where rectifiers have given such trouble is very small, and the cure is generally fairly simple. It is worth bearing in mind that the harmonic characteristics of rectifier plant are generally better understood than are those of the most prolific of interference causes, namely small motors, neon signs, etc. It is a much simpler matter to dispose of harmonic trouble on the d.c. side than on the a.c. side. Circumstances, however, reduce the risk of a.c. interference to negligible proportions in conventional rectifier applications, for the following reasons. The a.c. supply in the majority of cases in this country is given from a 3-core cable with the separate line-conductors in close proximity, so that for all practical purposes extraneous magnetic and electrostatic fields are non-existent. Communication apparatus connected directly to the a.c. system is fitted, as a matter of course, with filter gear, so that trouble from this source is unlikely. The d.c. side is, in general, and certainly with traction services, much more exposed from the interference point of view. The fairly wide separation of the live rail or trolley wire and the return circuit is bound to be more productive of adverse influence on neighbouring communication circuits. Nevertheless, the ease with which the d.c. harmonics can be removed obviates trouble on this score. Where rectifiers are supplied by an overhead line, interference is quite probable on neighbouring parallel communication circuits. Such a layout is, however, likely to prove troublesome quite independently of harmonics, and should always be avoided.

Mr. C. H. Brown: Dealing with the effects of a flashover on a glass-bulb rectifier, there is no reason why a fracture or any damage at all should result provided that proper anode fuses are fitted to the bulb, and there are on the market several good types of fuses adequate for this purpose. A large bulb protected only by wire fuses might be damaged by a flashover, but a similar bulb protected by proper fuses on the anode circuits, such as are now recommended by the various rectifier manufacturers, would not be affected.

This question of anode fuses is very important: such fuses not only give adequate protection for each bulb unit but also in the case of large multi-unit banks give discriminating protection, in that they will protect and isolate only the bulb unit affected. This in turn ensures that the duty thrown on a high-voltage switch controlling the primary supply to a glass-bulb rectifier equipment is no greater than that of a switch controlling an ordinary static transformer of equivalent capacity. The rupturing capacity of the high-voltage switchgear required is determined, therefore, only by the e.h.t. system requirements.

A useful feature of the glass-bulb rectifier is that a glance at the bulb is sufficient to determine whether the equipment is working satisfactorily.

Mr. H. de B. Knight: In his description of the Ignitron the author states that single-phase units are used for half-cycle welding. This may perhaps give the erroneous impression that the use of the Ignitron in resistance-welding control is restricted to welds of 1 half-cycle duration only. In practice it is usual to use two Ignitrons oppositely connected in the welding-transformer primary line, to pass both half-cycles of the a.c. wave. By suitable control any required duration of impulse may be obtained, from a fraction of a half-cycle to any number of cycles. The control is similar to that used in thyratron-controlled welders, and described, for example, by A. L. Whiteley,* except that the tubes, being capable of giving heavy peak currents, are connected direct in the line and no series transformer is required.

Several Ignitron-controlled welders of British manufacture are now in operation. For example, Fig. E shows the anode and anode lead of an all-steel Ignitron made in this country which takes the form of a water-cooled tube of approximately $3\frac{1}{2}$ in. diameter and is capable of giving a peak current of 6 000 amperes. Two such tubes will control a welder equipment giving 1 500-kVA impulses.

The author referred to the use of a special alloy, Kovar, for making connection to the glass insulating section. In the construction shown in Fig. E, use is made of a similar alloy, Fernico, whose expansion characteristic closely matches that of the glass used. The general dimensions and the problems involved in making the glass-to-metal seal will be appreciated from the fact that the lead to which the anode is fitted has a $\frac{7}{8}$-in. whitworth screw.

---

* *Journal I.E.E.*, 1936, vol. 78, p. 516.

Dr. C. C. Garrard: The most interesting feature of this paper is the description of the air-cooled steelclad rectifier shown in Fig. 2, which I think will find considerable application in the future. I should like to ask whether there is any limit of size for these air-cooled steel rectifiers. Simplicity is the first principle of engineering, and these steel air-cooled rectifiers are a very great advance towards simplicity inasmuch as water-cooling and the complications thereby involved are done away with.

With regard to the question of the rating of rectifiers, it is no use comparing the glass-bulb and the air-cooled steel rectifier on the basis of the normal rating; one must take into account the overload and short-circuit capacity. In this respect the air-cooled steel rectifier has many advantages, because it is capable of withstanding very heavy short-circuits and is therefore particularly applicable to heavy duty such as that met with on the London Underground Railways.

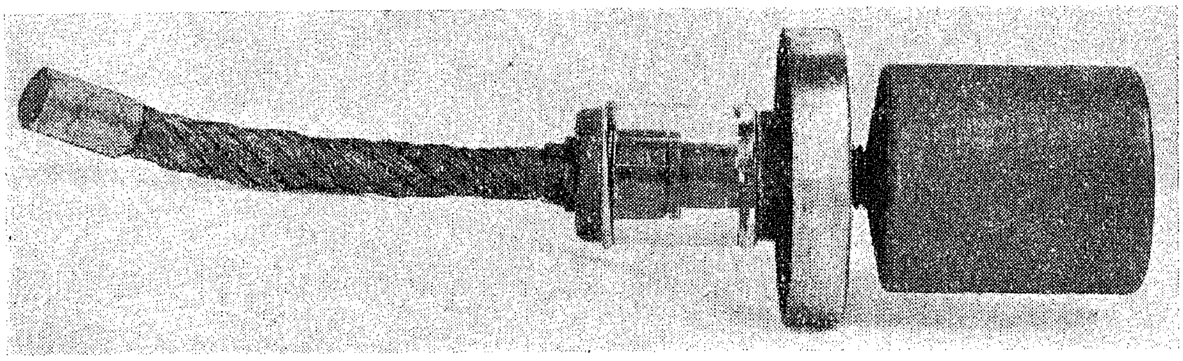


Fig. E

Twelve-phase rectifiers have been recommended as giving a d.c. output free from ripples; but the 12-phase rectifier will not give such an output, although it is better in this respect than the 6-phase rectifier. In searching for a means of avoiding ripples it is bad practice to introduce 12-phase construction of transformers, because the 12-phase transformer is much less reliable than the 6-phase transformer; I believe future standardization will be along the lines of 6-phase construction. More notice is taken of this question of ripples than is justified, because it is only in a few cases that the ripples in the d.c. voltage cause wireless interference. I think that each case of interference which occurs should be treated on its merits. If it is made a standard condition that the rectifier manufacturers shall guarantee the avoidance of ripple in the output of their rectifiers, the price of rectifier installations is bound to go up. It would be a good thing if this were made quite clear in the Specification for rectifiers which I understand is being prepared by the British Standards Institution.

Mr. W. R. Cox: From an examination of the paper and of British rectifier equipments in service one comes to the conclusion that, although the early commercial development of the mercury-arc rectifier took place more actively on the Continent than in England, the British-made rectifier of to-day is superior to its Continental equivalent. Probably the most useful field of use of the rectifier is for installation in substations, to supply traction systems of all types. Some of the characteristics of the equipment which make it so suitable for this work are: (*a*) Very high efficiency at the lighter loads. (*b*) Ease with which relatively high d.c. voltages (i.e. 1 500 or 3 000 volts) can be catered for. (*c*) Great stability on heavy load peaks. (*d*) Ease of remote control. (*e*) Low maintenance costs.

Of the types of rectifiers reviewed by the author the vacuum type in its various forms seems to have many advantages over the "jet" types. In the vacuum types one is dealing with a stream of electrons, which have very low inertia and are therefore not so difficult to control during heavy load fluctuations and under short-circuit conditions as are the "jet" types, which employ a relatively unstable stream of comparatively heavy liquid. The art of producing and maintaining a very high vacuum, which one might expect to prove difficult, has been brought to a high state of efficiency, and now that it is commercially possible to seal-off a metalclad mercury-arc rectifier completely a very simple and extremely robust piece of apparatus is available.

With regard to the author's remarks on Ignitrons, unless these can be permanently sealed and air-cooled there would seem to be a considerable disadvantage in the rather complex system of vacuum pipes and water-cooling pipes necessary, in each of which a number of insulated joints will be required.

[The author's reply to this discussion will be found on page 468.]

TEES-SIDE SUB-CENTRE, AT MIDDLESBROUGH, 6TH APRIL, 1938

Mr. H. V. Field: The mercury rectifier is in a rather unique position as compared with rotating plant, in that its efficiency is practically independent of size; in addition, its cost per kVA decreases very slowly with size. Hence banks of small units in parallel can compete quite effectively with a single unit of the same total rating.

The very satisfactory application of rectifiers to traction work is partly due to the use of series motors, in which the series field acts as a smoothing choke. If shunt motors were employed, the operation would not be so satisfactory unless considerably more smoothing equipment was provided at the rectifier.

Will the author explain why it is difficult to interrupt short-circuits on the d.c. side by grid control: is this problem affected by the de-ionization rate in the arc stream? Also, why are high-speed circuit-breakers still necessary on the d.c. side?

I notice that graphite has now replaced iron for anode construction. Does the lower thermal conductivity of the graphite reduce the anode rating as compared with an iron anode of the same size?

On page 449 the author states that the problem of increasing the number of phases is affected by the small commutating e.m.f. available with a large number of phases. Presumably this difficulty would be more troublesome on low-voltage rectifiers than on high-voltage types.

In the early days of electrical engineering, alternators were designed without reference to wave-form, but operating experience coupled with theoretical considerations indicated the desirability of keeping the harmonic content to a low value. Similarly, early practice with grid-controlled rectifiers having an appreciable range of voltage variation seemed to ignore the influence of the high harmonic content on the d.c. side. Large and expensive smoothing equipment is now realized to be necessary in such cases, unless the equipment is modified so as to embody tap-changing and the grid control is relegated to the subsidiary purpose of smooth control between taps.

Mr. R. Kell: I propose to raise an old question in connection with the glass-bulb type of rectifier, and one to which I have not be able to obtain a definite answer, namely what is the average life of a bulb under normal working conditions? My experience of a batch of 14 bulbs over the past 8 years has been fairly satisfactory, and compares favourably with that obtained on other types of electrical plant. It is unfortunate that no allowance can be made by the makers for the old bulbs, apart from a small amount covering the cost of the mercury. The replacement of a bulb is therefore an expensive matter.

The experience referred to does not cover the remaining portion of the rectifier equipment, the design of which in the past does not appear to have been up to the usual standard. I have met with failures of coils and of the primaries of tap-regulating transformers due to insufficient inter-layer insulation; in each of three cases this insulation has comprised simply the double cotton cover of the turns themselves. Oil switches on the anode circuits have also failed, and are gradually being replaced by special fuses. I should be glad to have some information concerning the characteristics of these fuses.

I would suggest that no fuses be inserted for the protection of cooling-fan motors unless adequate inspection of the fuse contacts and the condition of the fuse wires is carried out, as their insertion introduces the element of single-phasing. If protection by fuses is considered necessary, advantage should be taken of the natural situation of the motor in the cooling air stream, so that it may be designed to run for considerable periods in the single-phase condition. An alternative would be to supply the motor from the d.c. side. A guard should be provided below the fan in order that an indication of the motor temperature may safely be obtained by hand.

I recently inspected a bulb which, while cold, gives off a pink light instead of the usual purple. When the bulb was loaded up, the light emitted became purple, with faint traces of pink. There is also, while cold, more hunting than in the past between this bulb and the one with which it is paralleled. Is this a sign of incipient failure of the bulb, and, if so, can the colour of the light emitted be taken as an indication of its condition?

THE AUTHOR'S REPLY TO THE DISCUSSIONS AT LONDON, NEWCASTLE, BIRMINGHAM, AND MIDDLESBROUGH

Dr. W. G. Thompson (*in reply*): I agree with Mr. Fairburn that the non-vacuum type of rectifier may have arrived too late, and its use in practice will depend upon the possibility of exploiting the property of reversibility without change of connections. There is still some scope for the rotary convertor, which incidentally can provide a convenient means of dealing with regenerated power. Mr. Fairburn's experience of the reliability of glass-bulb rectifiers, as compared with the steel-tank type, does not appear to bear out the general rule. In a number of cases glass bulbs have become a total loss, and the success of glass-bulb rectifiers rests partly on the quick delivery of spare bulbs in the event of trouble.

It is somewhat difficult to produce a specification that will cover all the requirements of a traction system, and the only basis of comparison between types of rectifiers is equivalent service conditions.

Mr. Fairburn's opinion that grid control is hardly warranted from an economic standpoint, is of interest. The main reasons for advocating grid control in connection with traction work are: to deal with arc suppression, and to produce a level compound characteristic for parallel running with rotary convertors. The question of higher rupturing capacities for switchgear used in connection with rectifiers has been explained by Mr. Wood in his communication to the discussion.

I am indebted to Mr. Fairburn for the additional details he has supplied about the Basle frequency-changer. The problem of the amount of rectifier load connected to the a.c. supply to the Berlin Underground Railways is difficult to dispose of in these few words. As I understand it, the position is that the total d.c. rectifier capacity of 170 000 kW will rarely approach full load under working conditions. The supply provided by the local power stations amounts to some 400 000 kVA, but there is at certain times an additional 400 000 kVA linked in from more remote stations to give an aggregate supply kVA of nearly 900 000. Thus the proportion of rectifier load, though admittedly high, may not be as large as appears at first sight. The suggestion that trouble would be experienced if the rectifier load exceeded 15 % of the total is not borne out in practice, possibly owing to the filter effect of the network, especially with loads connected in parallel on the a.c. side of the rectifier.

The position of telephone and radio interference is difficult to assess without reference to a specific case, as the interference depends upon the degree of coupling between the power line and the telephone line, i.e. the spacing and the number of miles they are in close proximity. Underground sheathed cables will be well screened and should not give rise to serious interference.

Dr. Garrard suggests that the outlet for rectifiers will be mainly traction work; in this connection the use of a small pumpless steel-tank rectifier, reverse-connected across a larger unit, would provide an admirable means of dealing with regenerated power. The prospects of d.c. transmission are not at all promising so long as many problems in connection with high-voltage d.c. switching and high-power invertors remain to be solved on a practical scale.

The 12-phase connection is of advantage when it is desired to eliminate the 5th and 7th harmonics from the a.c. side, but, in order to avoid the 11th and 13th, 24 phases will be necessary. Here it is a question of treating each case on its merits, and experience has shown that 6-phase connection is, generally speaking, adequate.

I would hesitate to define an upper limit to the size of the air-cooled pumpless rectifier, as such rectifiers have already increased beyond the range that was thought economically possible from theoretical considerations. Probably the overload rating of the pumpless rectifier is best regarded as being intermediate between the glass-bulb and the steel-tank types, but more approaching the latter.

Mr. Gallizia draws attention to the importance of rectifiers in connection with electrolytic plants; units up to 8 000 kW and voltages up to 1 200 volts have been used for this purpose, 800 volts being fairly common. A feature of the electrolytic service conditions are long periods of uninterrupted operation at practically full-load current, with rapid voltage-adjustment to deal with fluctuations in the back-e.m.f.'s of the electrolytic baths. This represents fairly arduous loading for the rectifiers, and minor adjustments are sometimes necessary after 2–3 years' service.

The problem of electrode wear in Marx valves has received much attention, and considerable improvement has been made upon the earlier results; it is doubtful whether the wear will ever be reduced to negligible proportions, but experiments have indicated that its influence upon the operation of the valves can be minimized. At 300 kV, currents will be comparatively light and Marx valves will provide a convenient means of inversion should the need arise.

The output range of the pumpless steel-tank type of rectifier is encroaching upon that of the water-cooled types; on the other hand, pumpless rectifiers are not likely to be made much smaller, mainly for economic reasons. There is no doubt about the robustness of this type of rectifier, and evidence shows that the pumpless types have withstood rough handling and adverse conditions that would have been fatal to any of the glass-bulb varieties.

The worst case of telephone interference which I have experienced was where telephone cables and rectifier pilot feeders were combined in the same multi-core cable. In these circumstances conversation was admittedly irksome, but by no means inaudible.

Mr. Gallizia draws attention to the short time that steel-tank pumpless rectifiers have been available. The delayed advent of this type was largely due to preconceived ideas about the vacuum-tightness of metal vessels. The fact that pumpless steel-tank rectifiers were first successfully developed in this country is a tribute to the application and resource of British industry. There is little doubt that the pumpless rectifier will have a great influence on the trend of rectifier progress. It may be of interest to record that since the paper was written the outputs of individual pumpless rectifiers have been further increased, and these types of rectifiers are now being applied to duties hitherto regarded as being restricted to water-cooled rectifiers.

With reference to the rating of rectifiers, it would seem that manufacturers on the Continent and in this country must ultimately come more into line, as the overload requirements will depend upon the service conditions.

Mr. Pick mentions the absence from the paper of the more detailed aspects of 2 000-kW rectifier progress. Such progress has, however, been made, particularly in connection with the use of graphite grids and a better understanding of internal operating conditions. It may be remarked that although Continental manufacturers have had some 30 years' experience of rectifiers, service results have shown that the British-manufactured rectifier is certainly as good as, if not better than, its Continental prototype. The point is that except when some completely new arrangement, such as the pumpless steel-tank type, is produced, progress is slow.

The assertion that 3 000 amperes is the optimum size of rectifier was clearly stated as a maker's claim, and what may hold good under loading and manufacturing conditions in America may not apply to this country. I do not think it would be safe to assume that this optimum gives the water-cooled steel-tank rectifier an advantage over the air-cooled steel-tank rectifier. Figs. 4 and 5 are not strictly comparable, as Fig. 4 deals with large low-voltage rectifiers, whilst Fig. 5 refers to small high-voltage units.

Alkalinity and acidity tests have been carried out in connection with rectifier cooling and the presence of oxygen in the circulating water, but it must be admitted that in many instances corrosion data are very conflicting, especially as superimposed leakage-currents are present in various parts of the cooling system.

It is quite possible to time Ignitron control by phase-shifting means, and this has been done in some instances.

The difficulties which are withholding the Marx-type rectifier from the market are that for traction voltages its arc drop is higher than that of the mercury-arc rectifier, and at the higher voltages there has been no insistent demand for large outputs.

It is not my experience that Pirani gauges have required continuous renewal and resetting in water-cooled rectifiers. I am not quite clear about Mr. Pick's ingenious suggestion for a 2-stage transformer, but similar devices have already been used to minimize harmonic effects and give the equivalent of 24- to 36-phase supplies.

Mr. Read's remarks about the reliability of invertors under the operating conditions prevailing in South Africa are noted with interest. It is felt, however, that the phase-swinging problem must be more apparent than real. In simplest terms, the successful operation of the control mechanism means that the speed of response of the phase-adjusting device is adequate. The movement can never be instantaneous, and the mechanics of the problem are somewhat analogous to those met with in large synchronous condensers, which also operate successfully at the end of a long transmission line. The confirmation that the basis of the application of regeneration is economic rather than technical is worthy of note, as also is Mr. Read's lucid exposition of the attitude to grid control in this country.

Mr. Read referred at Newcastle to the question of pinholes. Such pinholes obviously do not occur in the vacuum vessel itself, but may arise in the anti-corrosive coating applied to the water space and thus expose bare metal to the action of water and leakage currents. It is usually possible to devise trouble-free systems, but local water conditions may give rise to the difficulties calling for special treatment of the cooling water. The air-cooled rectifier with its minimum of auxiliaries will set the pace in the direction of reducing the number of auxiliaries associated with the water-cooled rectifier.

Mr. Browne suggests that smaller units should give increased efficiency. In the first place it is a question of the shapes of the arc-drop curves for different-sized units, and also overall economy is often the prime consideration; in this connection plurality of fans, relays, and phase connections should be minimized.

The question of each unit being a stand-by to the others can be carried too far; load-sharing and reliability can be achieved without pursuing subdivision to the extent demanded by the small size of the glass-bulb units. Mr. Browne claims the advantage of the enormous anode area resulting from the multiplicity of cylinders used in the glass bulb. Actually it would appear that the same reasoning pertains even in regard to the largest water-cooled rectifiers, where the arc is effectively distributed over each anode surface by means of openings in the grids. One is tempted to think that the extra-large aggregate of anodes provided in glass-bulb installations is needed to give the necessary reliability.

The question of floor space can be met to some extent by arranging the rectifiers in two tiers. On the other hand, it does put up the height of the building, so that the glass bulb will still show to a disadvantage when the kW output is considered in relation to the cubic capacity or cost of a building.

Pumpless steel cylinders have been tested under identical conditions to those of the glass bulb and have proved to be equally efficient. They have also been successfully employed in connection with the same specifications, without any sacrifice of transformer reactance, to give a low voltage-drop.

To suggest that the multiplicity of units gives increased reliability would only be valid when the units were of the same kind. Quality is as important as quantity, and in this connection there is no reason why the smaller number of steel cylinders in a given equipment should be less reliable than a large number of glass bulbs.

The suggestion that there is no advantage in increasing the size of the bulbs appears to represent purely the glass-bulb manufacturers' point of view, and is directly contrary to our experience with steel pumpless rectifiers. Mr. Browne claims that the vitreous-enamel seal used with the steel type of bulb is no more successful than the seal used in the glass-bulb type of rectifier. There is ample evidence, however, that the vitreous-enamel seal is vastly superior, and is so designed that the weakest material, i.e. vitreous enamel, is adequately reinforced by the mild-steel cone assembly. To quote examples, the stems leading through the vitreous-enamel seal have on many occasions received hammer blows and have always withstood them successfully; further, as an experiment the actual terminals have also been completely melted off by 50 times normal current under a short-circuit test without failure of the seal, which incidentally is also subjected to high temperatures during manufacture.

With regard to the working temperatures of the arms of glass-bulb rectifiers, in some types these arms appear dull red on overload, and unless this is solely due to the red-hot anodes it can be taken that the anode arms are considerably above 250° C. The whole body of the glass bulb may be an insulator, but this is certainly a disadvantage in that it tends to facilitate the building-up of static charges.

The switchgear used in connection with glass bulbs is, generally speaking, small or at least segregated, and therefore severe switchgear conditions are not encountered. If, however, glass-bulb rectifiers are called upon to perform some of the heavier duties there is no doubt that the same physical phenomena as are met with in connection with large metal rectifiers will be found to be present.

Claims have been made that the transparency of the glass is an advantage in that it permits the checking of the operation of the cylinders by visual means. The loss of this facility has never been felt in connection with steel-tank rectifiers, especially as the interpretation of the phenomena observed in the rectifiers is a matter for expert judgment.

Mr. Henderson draws attention to the question of smaller units in parallel which is mentioned in the paper. I would explain that the term "small" is used in a relative rather than an absolute sense; for example, we should consider 2 500 kW small as compared with 10 000 kW. Mr. Henderson suggests that the steel-tank rectifier has advanced in size: here again, even the 3 000-kW rectifier is certainly smaller than the 16 000-ampere types tried out on the test-beds some years ago.

There are a number of sets of pumpless rectifiers in industrial service which are running at full load for 24 hours per day. The kind of loading has made little, if any, difference to the behaviour of this type of rectifier.

The paper did not intend to associate arc-suppression and high-speed breakers with cold starting in the sense implied by Mr. Henderson. It is known that slight changes in the dimensions of the shields and grids of a rectifier make a considerable difference to its performance, especially if it is of the so-called non-starting type, i.e. the type requiring a positive bias on the grids. Mr. Henderson's experience of the favourable influence of grid control on the rectifier rating differs from the opinions put forward by Mr. Read, and also those suggested in the paper. I have had the recent opportunity of discussing these points with independent authorities and it would appear that both points of view are correct, the former one being more representative of Continental experience. This also applies to the question of grid control in relation to backfire circumstances: Mr. Henderson favours the prevention of a cut-off when a backfire occurs, whilst the alternative is to try to eliminate the backfire.

The arc-drop curves of Fig. 4 were merely intended to indicate the influence of tank size; I agree with Mr. Henderson that lower arc-drop figures are now possible.

In reply to Mr. Harris, the airtightness of the pumpless steel-tank rectifier is obtained by virtue of the quality of the materials used and the skill employed in the manufacture of the vacuum vessels. The rectifiers are given a comprehensive series of leakage tests, so that their reliability in service is assured. The supply of spare glass bulbs can only be regarded as an additional service for which the customer must inevitably pay in the long run. The cylinders of the pumpless steel-tank type can also be replaced, but these will have a high recovery value, which is all to the ultimate advantage of the purchaser: incidentally, the lack of opportunity for selling spare cylinders is a disadvantage from the manufacturers' point of view.

The cost of water-cooled rectifiers is nearly always higher than that of both glass and air-cooled types, except when large outputs are involved.

Mr. North discloses the truth about double tiers for glass-bulb rectifiers. The larger glass bulbs will have a limited life, and a greater risk attaches to their practical operation. I still feel that the air-cooled steel-tank rectifier offers a better proposition in these larger sizes. The nine anode arms mentioned in the paper are a peculiarity of that glass-bulb manufacturer's construction; it has been found that an increase in the useful life of the bulb can be achieved by changing over to the spare arms after a certain period of operation. There is no reference in the paper to a statement suggesting the corrosion of graphite anodes.

I am much indebted to Mr. Wood for his neat explanation of the possible cause of some of the switchgear difficulties encountered in switching off rectifiers under backfiring conditions. It is interesting to note that the stored energy in the closed current path shown in Fig. D is unidirectional, and as no reverse current flow takes place the grid control is not likely to have much influence in preventing the snap-out of the arc. Thus, under these conditions, arc suppression by grid control is less effective in reducing the duty on the circuit-breaker than is generally supposed.

I am also indebted to Mr. Lintott for his clear explanation of phase-shift with grid control, and am inclined to agree with his observations about tap-changing.

I am surprised to find that he is attempting to measure anode power, as this is a notoriously difficult quantity to measure with accuracy. The use of current transformers would seem to be inadvisable, because of the influence of the current-transformer magnetization resulting from the unidirectional impulses of the anode current. I would suggest that, rather than use a current transformer, a suitable shunt should be employed and the wattmeter insulated so as to avoid potential between voltage and current coils. I have also measured the power in a single anode circuit, but have not encountered the pulsations referred to by Mr. Lintott. Their cause is more likely to be found in some inconsistency in the metering circuit rather than in the performance of the rectifier. So far as plurality of grids is concerned, it is extremely unlikely that mercury-arc rectifiers will be fitted with more than two grids for normal working purposes.

In reply to Mr. Beaty, the maximum current which can be taken from a 100-kV air-blast rectifier under polyphase conditions is comparatively small, not in consequence of the limitation of the rectifier but owing to possibilities of dissipating the load at that voltage; up to 90 amperes have been carried by a single-phase unit and, judging by the performance of an air-blast rectifier set-up at 20 kV, there should not be much difficulty in rectifying a heavy current at even higher voltages.

The pumpless rectifiers referred to in the paper are of all-metal construction and are not dependent upon any covering, internal or external, for the maintenance of their vacuum. In connection with grid control, up to 300 volts negative bias is fairly common.

I am glad to have Mr. Royle's encouraging remarks concerning the very high standard of performance and reliability of the water-cooled rectifiers installed at Sunderland, and particularly his mention of practically negligible maintenance costs. Relays for the protection of such rectifiers were fitted on a fairly elaborate scale in the past, but no doubt these will tend to become fewer in the future. The backing pump is required to provide the low back-pressure to enable the diffusion pump to function correctly.

The ignition method mentioned by Mr. King is quite practicable and is largely used on the Continent. Its opponents claim that there is a possibility of locally ageing the glass with several restarts.

In reply to Mr. Gibson, the position of d.c. transmission may be summed up as follows: (1) The saving on d.c. overhead lines is far less than is usually anticipated. (2) Direct-current transmission is inferior to alternating-current so far as reversibility of power is concerned. (3) The extra cost of the rectifiers is not compensated by savings in other ways. (4) Suitable means of switching have yet to be devised. (5) The wattless-current problem at the load end is much more acute than in the case of a.c. lines. (6) Even for long-distance transmission, the d.c. power loss due to voltage-drop is such that it becomes worth while to sectionalize the d.c. line, and the system therefore has no advantage over the usual sectionalized a.c. system with power-factor correction.

If igniter-type rectifiers are required to operate continuously it is also necessary to run the auxiliary valves continuously.

In answer to Mr. Baker, the factors leading to the distress of rectifiers on heavy loads are increased vapour pressure due to temperature-rise, and a slower dielectric recovery rate due to delayed de-ionization in front of the anodes. Temperature control of air-cooled rectifiers is already automatic to some extent by virtue of fan-speed control. In the event of a rectifier being called upon to operate in extreme climates, some means of preheating the air could be adopted.

Mr. Kerr raises the question of brush-wear and other problems relating to traction motors supplied with direct current from rectifiers. Experience both on the test-bed and in service has shown such supplies to be entirely satisfactory for all types of d.c. motors.

In reply to Mr. Manighetti, the rating of rectifier switchgear has been arrived at largely as a result of experience. Mr. Wood has given a comprehensive explanation of the problem in his contribution to the discussion, but it remains to interpret the phenomena in terms of the nominal rupturing capacity by which switches are usually rated.

The errors in indicating power-factor meters have been under investigation for some time; providing the harmonics are confined solely to the current or to the voltage, the meter should not be adversely affected. Where the same harmonics are present in both voltage and current, a small correction will be necessary depending upon the principles on which the design of the power-factor indicator is based. As far as traction metering is concerned, load fluctuations are usually so severe that metering might be confined to the a.c. side.

The cost per kW of rectifier equipment varies considerably, being as low as £2·5 in some cases and over £10 in others. Under equal conditions and for moderately large power, the water-cooled, pumpless steel-tank, and glass-bulb types may be regarded as competitive.

The earlier difficulties met with in rectifier development, mentioned by Mr. Patterson, have now been largely overcome. I cannot agree that breakers whose speed of break is adequate to deal with rectifiers in parallel have yet to be constructed. Investigations dealing with accurate measurements of the rate of operation of high-speed breakers have been made, and there is no indication that the limits of high-speed operation have been reached. It is largely a matter of cost, for the installation of a separate breaker for each rectifier on the d.c. side would prove too expensive.

The modern tendency is to use suitable anode fuses or alternatively to design the rectifier to withstand the short-circuit current and rely on the fast operation of a.c. and d.c. breakers of conventional design. The re-forming trouble mentioned in the discussion does not arise in the case of pumpless rectifiers, as these are always thoroughly degassed before they leave the works.

I should like to endorse Mr. Taylour's remarks about grid control. With regard to cables and d.c. transmission, the cost of cable per mile is about 5 times that of overhead lines, except in city areas, so that it is difficult to see what advantage would accrue from a general d.c. transmission scheme making use of cable. It might just be possible to use cable for d.c. transmission across a large city, such as London, but it is considered that such opportunities will rarely present themselves.

Mr. Taylour gives a particularly good summing-up of the harmonic problems from the interference point of view, and there is little that can be added without going into great detail.

I am very interested in Mr. Brown's remarks regarding the protection accorded to glass-bulb rectifiers by the use of anode fuses. In practice we have one great criticism to meet, namely that while it does give a measure of safety it is likely to prove expensive where large installations are involved. The situation is also embarrassing when the origin of the short-circuit is not clear and the fuses are replaced by a new set, which may blow immediately. There is no doubt that fuses will remain the chief link in the protection of small rectifier equipments, but in the case of larger units it is probably advisable to capitalize expenditure in terms of more robust rectifier units and better switchgear.

I am indebted to Mr. Knight for his interesting information in connection with Ignitrons; glass seals have also been made for experimental work in connection with pumpless rectifiers for various sizes. Such seals have been manufactured up to 12 in. diameter, but in actual practice the vitreous-enamel seal is much to be preferred.

In reply to Mr. Cox, there is no doubt that the British rectifier, particularly the air-cooled pumpless type, is in a number of ways far in advance of Continental development, and the success of many equipments in service overseas justifies the confidence placed in the British product. The success of the sealed-off Ignitron will depend upon the type of seal available. Another point is that any foreign matter such as carborundum or porcelain needs thoroughly degassing before being brought into contact with the mercury, to avoid the formation of contaminating matter on the mercury surface. I think there is little doubt that eventually the pumping system will be eliminated on large Ignitron rectifiers.

Mr. Field remarks on the influence of cost per kVA and rectifier efficiency in relation to the size. It is agreed that banks of small units in parallel can compete effectively with the single unit at the same total rating, but there are times when the multiplicity of components involved leads users to prefer single larger units on the grounds of simplicity

So far we have been able to detect very little difference between the performance of series and shunt motors when running on rectifier supply. The series field, however, has comparatively low inductance, while on the other hand the shunt field provides a parallel path which may tend to ease any troubles at the commutator. Graphite anodes have a lower thermal conductivity and thus reduce the warming-up period.

Rectifier commutation is better, if anything, on high voltage, because (*a*) there are more commutating volts available; (*b*) the current, and thus the intensity of ionization, is usually smaller; on the other hand, the voltage recovery rate may be slightly higher.

Further to Mr. Kell's remarks, the average life of a glass bulb under normal conditions depends upon how the manufacturer rates his product. It is generally understood that, where the loading of glass bulbs is increased in order to lower the cost of the total equipment, the life of each bulb will be proportionately less. Setting aside purely accidental damage, a liberally rated glass bulb has been known to last 10 or more years. On the other hand, where the loads have been unduly high, bulbs have failed in less than 5 years. Mr. Kell comments on the fact that there is practically no allowance for old bulbs; this point has been dealt with in the reply to Mr. Browne.

With regard to replacing switches by fuses, this is discussed in the reply to Mr. Browne's remarks. The question of the single-phasing of fan motors has not so far arisen in connection with rectifiers with which I have been associated. The remedy would appear to lie in the use of a suitable form of motor: it is almost universal practice to protect small 3-phase motors with fuses, and the rectifier duty should not alter operating conditions to an extent sufficient to warrant departure from standard practice.

The colour of the light emitted from a glass bulb can be taken as an indication of vacuum conditions, but the diagnosis is usually a matter for expert opinion. The pink light is of interest, as the change from the pink to the violet light takes place during " forming " of the rectifier, and is generally regarded as a sign of the improvement of the vacuum.

In connection with the failure of coils, the importance of small parts is not always appreciated by those directly engaged in making those parts; also such troubles are not confined to rectifiers, nor to one group of manufacturers, but are largely the result of the severe competitive price conditions both in this country and abroad.

With regard to the transformers being insulated with double cotton covering, it would appear this is a matter of incomplete specification and is not a method of insulation which would be approved by any manufacturer of repute.

PLASTICS AND ELECTRICAL INSULATION

By L. HARTSHORN, D.Sc., N. J. L. MEGSON, M.Sc., and E. RUSHTON, B.Sc.

[From the National Physical Laboratory and the Chemical Research Laboratory.]

(*Paper first received* 1*st November*, 1937, *and in final form* 21*st February*, 1938; *read at a Joint Meeting of* THE INSTITUTION *and the* PLASTICS GROUP OF THE SOCIETY OF CHEMICAL INDUSTRY 24*th March*, 1938.)

SUMMARY

The paper is submitted to a joint meeting of plastics chemists and electrical engineers as a contribution to a general survey of the field in which their activities meet. It consists of the following parts:—

(i) A brief discussion of dielectrics and the factors which represent their value to the electrical engineer.

(ii) A discussion of the essential nature of plasticity, and of the characteristics which the chemist has to produce when synthesizing plastics for the moulding industry.

(iii) An experimental investigation of the properties of synthetic resins of the bakelite type, and the way in which their electrical properties may be affected by chemical and physical factors.

(iv) A brief discussion of the various synthetic plastics now available, and of such of their properties as are of importance in electrical practice, with some general conclusions as to lines of research which may be expected to yield results profitable to both the industrial chemist and the electrical engineer.

(1) INTRODUCTORY

In presenting this paper the authors' primary object is to stimulate a discussion on matters of common interest between two widely different groups of workers: electrical engineers and chemical technologists. It is generally recognized that among the technical problems with which the electrical engineer is faced, those presented by insulating materials are of outstanding importance. Progress in many directions would become possible if the limitations of existing materials could be overcome, and as a result electrical engineers in all branches of the industry are constantly seeking new dielectrics.

On the other hand, nothing is more characteristic of the trend of modern industrial development than the widespread use of moulding as a manufacturing process, based on those developments in chemical technology which have made it possible, namely the synthesis of plastics. The plastics technologist does not primarily set out to serve the electrical industry. He finds that some of his products are welcomed by the electrical engineer as insulating materials, and that they are incidentally subjected to tests of an extraordinary complexity, which have no immediately obvious connection with the chemical factors which lie within his own control. As the skill of the plastics technologist and our knowledge of the chemistry of plastics increases, however, it will surely become possible to synthesize products having just those qualities desired by the electrical engineer. It is therefore of the utmost importance that the plastics technologist and the electrical engineer should confer, and at least take a preliminary survey of the field in which their activities meet. It is hoped that this paper will serve as the starting-point of such a survey.

It is obviously desirable that a broad and somewhat distant view should at first be taken, and the authors are therefore concerned only with what may be termed the research point of view. They are not concerned with classifications, specifications, and methods of test, which have already been adequately treated in a recent paper by Dunton and Caress.* From the electrical side it is necessary to try to discover the essential nature of the processes which occur within any material employed for purposes of electrical insulation. We also require to know whether the limitations of existing materials are linked with their chemical purity, the structure of their molecules, or atoms, or the way in which the molecules are packed and held together. From the chemical side we must note the great range of materials which the plastics technologist has been able to produce and the factors which may be controlled with the chemical technique now available.

The situation having been viewed from both sides, an attempt must be made to indicate in which direction the search for better insulating materials is likely to be most profitable.

It need scarcely be said that the task is of such a magnitude that any attempt in the form of a single short paper is bound to be imperfect, incomplete, and indeed only a fragment of the full inquiry which the situation calls for. All that this paper pretends to accomplish is to outline for the benefit of the plastics chemist the significance of the basic electrical properties, to indicate to the electrical engineer the chemical nature of a plastic and the possibilities of controlling it by chemical technique in directions which may interest him, and to illustrate these points of view with some researches carried out by the authors, which are presented as part of the general framework outlined above. Many gaps will still remain to be filled. The treatment of the introductory matter has been made as elementary as possible in the hope that it may introduce the subject to workers whose specialized interests lie in widely different fields.

(2) THE NATURE OF A DIELECTRIC

The primary function of an electrical insulating material (dielectric, for short) is to act as a barrier to the flow of electricity, and all the various dielectric properties used by engineers merely represent the efficacy of the material as an electrical barrier considered from various points of view. The familiar analogy with the flow of water may be helpful. A conductor at high voltage is analogous to a volume of water at high pressure. The water flows outwards in all directions unless the flow is opposed by barriers (the walls of tanks or pipes) capable of withstanding the pressure. A layer of insulating material on the surface of a conductor at high voltage is therefore analogous to a diaphragm closing an aperture in the side of a tank of water at high pressure. If the pressure of the water is steadily increased, a point may be reached at which the diaphragm will burst, and the pressure at which this occurs will provide one obvious measure of the effectiveness of the diaphragm as a barrier. Similarly, if the voltage applied to a dielectric is steadily increased, a point is reached at which the electric barrier bursts. There is a sudden rush of current through the material which completely ruins it, and the voltage at which this occurs obviously measures the effectiveness of the material as an insulator from one point of view. Thick layers would obviously withstand a higher voltage than thin ones, and therefore when comparing different materials we consider the voltage per mm. or mil of thickness at breakdown, which is termed the electric strength of the material. Our diaphragm in the side of a tank of water at high pressure might, however, give trouble before the bursting pressure was reached. It might leak more or less seriously even at low pressures, not sufficiently to put the tank out of action, but enough to be a nuisance. Moreover, the leak might occur on account of the porous nature of the material of the diaphragm, or merely at the edges owing to imperfect jointing. In a similar way dielectrics always pass a leakage current, sometimes through the body of the material and sometimes over the surface. These defects of the material are measured by the leakage current per unit voltage in the two cases, i.e. by the volume or surface resistance, or, if we consider the values corresponding to a centimetre square of surface or a centimetre cube of volume, we obtain the surface and volume resistivities as quantities representing the tendency of the material to leak in these two ways.

---

* *Journal I.E.E.*, 1936, vol. 79, p. 463.

The diaphragm we have considered might, however, give trouble in another way, in conditions analogous to those of electrical practice. For electrical pressures are usually alternating or pulsating, and if the pressure of the water is made to pulsate, say, 100 times a second, the diaphragm will certainly be set into vibration, and owing to its imperfect elastic properties it may become hot, especially if the vibrations are of large amplitude and the frequency is very high. The energy lost as heat in this way may or may not be serious, but the rise in temperature may very seriously lower the bursting pressure, and also increase the leakage. A dielectric in an alternating field dissipates energy in an analogous manner. Just as the diaphragm yields slightly when the pressure is first applied, so the dielectric permits a displacement of electricity. The dielectric constant, or permittivity, of the material measures the amount of this displacement for a given electric force. The diaphragm resumes its normal position when the pressure is removed. Similarly, the electric displacement vanishes when the voltage is removed, but in both cases the energy expended in making the displacement is not wholly recovered when the barrier springs back. The ratio of the energy lost to the energy expended in each pulsation is measured by the power factor. It is easy to see that the total energy lost and the consequent rise of temperature will increase as the dielectric constant, the power factor, and the frequency, increase.

This effect is much more serious in dielectrics than the mechanical analogy might suggest, and it may happen that the permittivity and power factor are even more important to the engineer than resistivity and breakdown voltage.

In addition to these purely electrical properties, plastics must of course possess good mechanical and thermal properties. They must be strong in tension and compression, not unduly brittle, and not liable to swell or shrink under working conditions. These properties are, however, not peculiar to electrical applications, and need not be considered here in detail.

It may perhaps be advisable to point out that there is no single property of a material which can be taken as a criterion of its electrical performance under all conditions. For high-voltage work, electric strength must receive first consideration (but here again it must be noted that the breakdown may be of a surface character). On the other hand, a telephone engineer will not be much concerned with the electric strength of the materials used in his cables. He has to transmit minute electrical vibrations of high frequency. He will therefore be seriously concerned about leakage, dielectric constant, and power factor. He desires a low dielectric-constant and a low power-factor. On the other hand, a low dielectric-constant is not always required. A condenser-maker requires a high dielectric-constant with low power-factor, for a condenser is essentially a device to permit the passage of large electrical oscillations (or alternating currents) with little loss of energy, and, as we have seen, the amplitude of the electrical oscillation is proportional to the dielectric constant. The properties of each material must be considered in relation to its possible application.

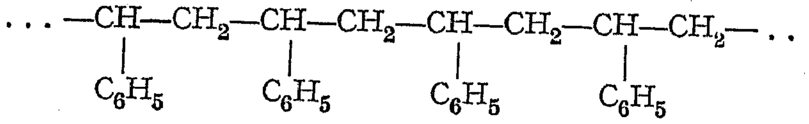
(3) THE NATURE OF A PLASTIC

A plastic is, broadly speaking, any material from which rigid objects of predetermined shape may be made by moulding processes. The most characteristic property of plastics is that by suitable treatment they may be made to pass through a plastic condition, i.e. a state intermediate between the solid and liquid states, like that of dough or damp clay. Every child knows by practical experience how admirably this condition is suited to the moulder's art. For our present purpose it is necessary to understand the relations between the chemical and physical structure of a material and the possibility of its attaining the plastic condition.

The molecules of a material in the solid state must be regarded as locked together in a rigid structure by the attractive forces between them. Although locked together, the molecules are in a state of vibration, and as the temperature rises the vibration increases until at a certain temperature the attractive forces can no longer keep the structure intact. If heat is steadily supplied first one molecule and then another acquires sufficient energy to overcome the attractive forces, and these molecules take up new positions of equilibrium in which the forces binding together adjacent molecules are very much smaller. Energy is required in order to overcome the original strong forces, and therefore the temperature of the body does not rise until all the molecules have taken up sufficient energy to make equilibrium possible in the new positions. In other words, latent heat is absorbed until the whole of the original structure has been shaken loose, and the material has become a liquid.

The solid body has a definite shape and is able to withstand the action of large applied forces tending to change its shape: the liquid has a definite volume but no definite shape. The smallest forces, suitably distributed, are sufficient to cause continual changes of shape. The solid behaves as though its molecules were fixed in definite positions in the structure. The liquid behaves as though its molecules were capable of sliding freely over one another so long as the displacement does not alter the average distance between them and therefore the total volume. In the plastic condition a body may have the definite shape of the solid, but the resistance it offers to stresses tending to change that shape is very much smaller than in the case of the solid and larger than in that of the liquid. Thus a material of a laminated type of structure would be plastic if the forces holding together adjacent molecules in different layers were very much weaker than those between adjacent molecules in the same layer. The layers are easily made to slide over one another and thus the body is able to accommodate itself to changes of shape, while still keeping the structure intact. The plasticity of graphite, soft metals like tin, and possibly clay, is believed to be of this nature, but these materials are not plastics of the type we are discussing. The materials of the plastics industry show no evidence of a simple laminated type of structure, and indeed very little evidence of crystal structure of any kind. They have the plasticity of resins and gums, which pass gradually into the plastic condition when the solid material is heated. We have seen that when heat is steadily applied to a solid of regular structure, i.e. a crystalline solid, the temperature remains constant from the point at which the structure begins to break to the point at which it is all broken; in other words, the crystalline solid melts at a definite temperature with the absorption of latent heat. But when heat is steadily applied to a plastic, no such melting-point is observed; the rise of temperature is continuous, but over a somewhat indefinite range of temperature (between those characteristic of the liquid and solid conditions) the material has plastic properties.

It is well known that the presence of impurities in a material usually makes the melting point less definite: melting occurs over a small range of temperature instead of at a definite point. The foreign molecules probably introduce forces of a different magnitude into the system, and thus the energy of thermal agitation required to loosen the structure is not constant for all parts of the structure, and certain parts only become loosened after the temperature has risen somewhat. An obvious extension of this idea suggests that plastic properties may arise when the molecules of the material are not all exactly similar, but are subject to variations which cause corresponding variations in the forces between adjacent molecules throughout the structure of the solid. Over a certain range of temperature, thermal agitation may be sufficient to loosen parts of the structure but not the whole of it, and therefore we get the semi-rigid structure of the plastic. From these considerations one would expect to find plastic properties in any intimate mixture of a graded series of similar compounds, e.g. a mixture of isomers, or molecules containing the same numbers of atoms of various kinds but with slight differences in their arrangement, and it is probable that the plastic properties of, say, the chlorinated diphenyls [see Fig 1(*b*)] arise in this way. Again, paraffin wax is an intimate mixture of a graded series of similar hydrocarbons, and it is conceivable that its rudimentary plastic properties are also of this nature. Paraffin wax is not, technically speaking, a plastic, but the molecule of polystyrene, which is a typical plastic, has a sufficient resemblance to those of paraffin wax to suggest that its plasticity is due, at least in part, to similar forces. In both materials the molecules consist of long-chain hydrocarbons, and in polystyrene as in paraffin wax it is probable that we have a mixture of chains of various lengths. The hydrocarbon chains are very much longer in polystyrene than in paraffin wax, and they are also loaded at intervals with benzene rings, thus:—



$$\ldots -\underset{\underset{\textstyle C_6H_5}{|}}{CH}-CH_2-\underset{\underset{\textstyle C_6H_5}{|}}{CH}-CH_2-\underset{\underset{\textstyle C_6H_5}{|}}{CH}-CH_2-\underset{\underset{\textstyle C_6H_5}{|}}{CH}-CH_2- \ldots$$

It is therefore not surprising that the plastic properties of polystyrene are more pronounced than those of paraffin wax.

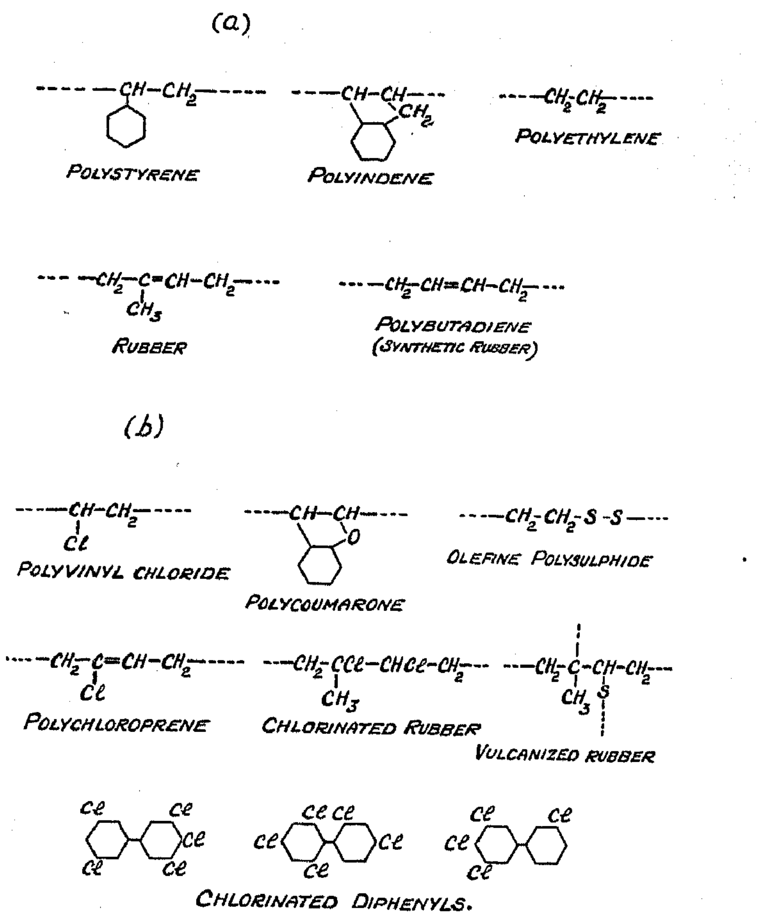


Fig. 1.—Characteristic units in the structure of (*a*) hydro carbons and (*b*) substituted hydrocarbons.

The molecules of polystyrene may be of such a length as to contain 20 000 carbon atoms. It is to be expected that these long thin threadlike molecules will in the ordinary way be coiled and intertwined in a somewhat irregular manner, and such an arrangement might be expected to have plastic properties even if the molecules were all of the same structure, so that the material was a pure chemical compound. For, unlike the ordinary small molecule, the long molecule may have several points of attachment to neighbouring molecules. The application of heat imparts energy of vibration to the molecules, but the molecule is able to take up so many different configurations and corresponding modes of vibration, that as heat is supplied it is no longer necessary for it to jump from the position corresponding to the solid to that corresponding to a liquid as soon as its energy reaches a certain value. When the thermal agitation is sufficient to break some of its points of attachment, the molecule changes its configuration and modes of motion, so that it is still able to carry the additional energy of vibration but at the same time to maintain a few strong points of attachment to neighbouring molecules. The structure therefore does not break down at a definite temperature but gradually loosens as the temperature rises.

The plastic condition may therefore arise in various ways, but it will be clear that the most favourable conditions for the production of resins are those which permit the formation of molecules having many possible configurations and modes of vibration, and also of many molecules of similar construction but varying in size. Both of these conditions are satisfied by large complex molecules of a flexible character, such as can be built up on the unit principle, like the making of chains of various lengths from links of a standard size, or the assembling of an expanding bookcase, which may expand in several directions. Other things being equal, one might expect that the attainment of the desired condition would require larger structures of the plain chain type than of those having projections. Thus, although a typical molecule of polystyrene may contain, say, 20 000 carbon atoms, molecules of this size are not essential to resin formation. Much will depend on the configuration of the unit, and the number of active points on it, i.e. the number of points on it at which attractive forces are concentrated. Broadly speaking, however, the art of the plastics chemist consists in the building-up of large molecules from simpler units, and his success has resulted in the production of a great range of synthetic resins, many of which possess very valuable electrical and mechanical properties. Materials with molecules of these types were found in nature long before the days of synthetic resins, and it is significant that since the earliest days of the electrical industry among the materials most widely used have been the natural plastics—shellac, bitumen, gutta percha, rubber, rosin, and amber.

(4) ELECTRICAL PROPERTIES AND STRUCTURE

It is impossible to examine the relation between the electrical properties of plastics and the chemical and other factors governing their production without some reference to the physical chemistry of dielectrics in general, and to recent theories of dielectrics. Detailed surveys of these fields have been made by one of the authors* and by W. Jackson.† It is merely necessary to give here a very brief sketch of those parts of the subject which are applicable to plastics.

The most obvious fact bearing on the problem of the connection between dielectric properties and structure is that these properties are not simply determined by the kinds of atoms which a material contains. The metals possess no insulating properties; on the other hand, mica, which is an excellent insulator, contains atoms of potassium, magnesium, aluminium, etc. There is, however, ample evidence of a connection between insulating properties and molecular structure. All the hydrocarbons are good insulators, while substitution products of high dielectric-constant (alcohols, acids, esters, etc.) are greatly inferior to the corresponding hydrocarbons. Water is particularly bad, and is so much the bugbear of the electrical engineer that it will be considered in detail later.

These facts have, to some extent, been explained. Thus water, alcohol, nitrobenzene, and other liquids of high dielectric-constant tend to ionize materials dissolved in them. The force of attraction between two oppositely-charged particles varies inversely as the dielectric constant of the surrounding medium. Thus such particles are comparatively loosely held together in water, etc., and therefore any molecule containing parts charged positively and negatively, held together by electric attraction, tends to separate into two oppositely-charged ions, on immersion in such liquids. Any electric force acting on such a material causes the two kinds of ions to drift in opposite directions along the lines of force, and it is this drift which constitutes the leakage current. Surface leakage is usually due to the motion of ions in an adsorbed film of water on the surface of a solid material. Ionic currents may also flow through solid materials, but it is to be expected that the motion of the ions will be more restricted than in a liquid. Nevertheless, the leakage current in bodies like glass is known to be largely ionic in character, and it is quite probable that this is also true of synthetic resins, especially those prepared with strongly ionized catalysts like HCl. The phenomenon of electrical breakdown (electric strength) in resins may also be explained by these ionic currents. The mobility of the ions is greatly increased by a rise in temperature, and as the voltage is increased the heat generated by the ionic current raises the temperature, so that the current increases more and more rapidly until an unstable condition is reached and the material is melted or decomposed at the hottest spot. Such an action might obviously occur in the adsorbed film on the surface of a solid, and it is found that conducting paths are sometimes burnt on the surface of a solid in this way (tracking).

The phenomena associated with dielectric displacement (dielectric constant) and power factor require further consideration. We have stated that the dielectric displacement, which is proportional to the dielectric constant, is analogous to the mechanical displacement of an elastic diaphragm. Thus, it must be of the nature of a movement of electricity which reaches a definite value the instant the electric force is applied and remains at that value until the force is removed, when the movement is reversed and the original condition restored. It is to be remembered that all matter consists of positive and negative charges locked together in a more or less stable equilibrium by the attractive forces between them. When the electric force is applied, the positive and negative charges tend to move in opposite directions and are displaced until the increased attractive forces called into play prevent further motion. This provides an adequate explanation of the electrical displacement in materials of low dielectric-constant, but the high dielectric-constant of materials like water and alcohol diminishes very rapidly with rise of temperature, a fact which is quite inexplicable in terms of the electric distortion of the molecules described above. Electric displacement may, however, also arise from the rotation of molecules as a whole. If the positive and negative charges constituting a molecule tend to be concentrated at opposite ends, then, although the molecule as a whole is neutral and will not drift in the field like a single ion, it will possess positive and negative electric poles analogous to those of a magnet, and will turn in the electric field like a magnet in a magnetic field. This rotation of a polar molecule constitutes an electric displacement. Materials like water, nitrobenzene, and alcohol are polar in this sense. Their high dielectric-constant is almost entirely due to molecular orientation. The diminution of dielectric constant with rise of temperature is explained by the effect of thermal agitation, which tends to cause a random motion of the molecules and to prevent an orientation in one particular direction. Such molecular rotation may also be opposed by forces of viscosity, and these may account for the loss of power when the molecules are set in vibration at high frequency—in other words, for the power factor of the material.

---

* L. HARTSHORN: *Journal I.E.E.*, 1926, vol. 64, p. 1152; and *Reports o Progress in Physics* (published by the Physical Society), 1936, vol. 3, p. 206.

† W. JACKSON: *Journal I.E.E.*, 1936, vol. 79, p. 565.

Thus it is to be expected that the dielectric properties of a material will depend largely on its molecular structure. Materials with polar molecules will possess relatively high dielectric-constants, but probably high power-factors. There is, however, considerable evidence to show that molecular structure is not the only factor controlling the electrical properties of a material. The effect of macro-structure must also be considered. Suppose, for example, that a body consisted of a number of conducting particles embedded in a perfect insulating medium. Such a body would show no leakage current. On the other hand, on applying the electric force, ions would move within the conducting particles, the positive and negative charges collecting at either end, and when the force was removed these ions would move back under the influence of the field produced by the displacement of their charges. Thus the motion would constitute an electric displacement, and if the frequency was high the energy dissipated in the particles might be considerable, and we might have a dielectric with zero leakage but high power-factor. This theory is obviously applicable to composite materials, such as a moulding made with a resin and filler, or a laminated board, and a somewhat similar idea has also been advanced to explain the power factors of apparently homogeneous materials. It has been suggested that all materials, even crystals, are subjected to certain irregularities of structure. The crystal is conceived as a kind of mosaic structure of small perfect units (of, say, 10^4 molecules) separated by surfaces of discontinuity. Absorbed moisture is held in the spaces between the units, and ions are to be found there. The ions may be either free or adsorbed on the surfaces of the units, and therefore capable of moving over a surface but not leaving the unit to which they are attached. Such ions will evidently give rise to electric displacement and power loss under alternating voltage, while the free ions give rise to leakage.

(5) EXPERIMENTS ON PHENOLIC RESINS

General

We now proceed to an experimental study of synthetic resins of the phenolic type and the heat-hardening variety. This type of resin was selected for examination since it is the one most widely used in the electrical industry. As is well known, it is used in conjunction with paper or fabrics to form laminated boards of great mechanical strength, while in conjunction with finely-divided materials ranging from wood to mica it forms moulding compositions which have valuable electrical and mechanical properties, and which are relatively cheap. It must, however, be admitted that the use of these materials in communication engineering is limited by their power factor, which is seldom less than 0·02 and often considerably greater. It is therefore important that we should find out how much of this power loss is due to the filling material, and how much to the pure resin; and whether the loss in the resin itself is due to impurities or to variations in manufacturing processes, or is inherent in the structure of the resin. For this purpose, measurements were made of the dielectric constant (permittivity) and power factor of a series of specially-prepared pure resins under various experimental conditions.

The resins were examined in the form of thin films. Details of their preparation have been published elsewhere.* It is sufficient to state here that sheets of copper foil were coated on both sides by being dipped into alcoholic solutions of the resin, heated at 80° to 90° C. for some hours, and finally stoved overnight at 150° C. By repeating the process, films of any desired thickness were built up. The sheet with its double film was supported in a conditioning enclosure by the arrangement shown in Fig. 2. The faces of the clamps are recessed, and the recesses can be either flooded with mercury, thereby providing the samples with mercury electrodes for testing, or swept out with dry air at reduced pressure. It will be evident that the condition of the sample could be varied and tests made at any stage of the process without disturbing the sample in any way.

The experiments showed that under ordinary conditions the pure phenol-formaldehyde resin has a power factor of 0·013 (at a frequency of 1 000 cycles per sec.), and a dielectric constant of 4·7. The variations of these quantities among samples prepared on different occasions amounted to about ± 10 %, but within these limits the values were the same for films of all thicknesses from 0·03 to 0·2 mm., and for resins prepared with various catalysts (ammonia, triethylamine, and pyridine). Moreover, the deliberate addition of various likely impurities had no very large effect. The effects of adding 0·7 % by weight of " hexamine " or 2·5 % by weight of phenol were negligible, while 0·5 % by weight of caustic soda increased the dielectric constant to 5·1 and the power factor to 0·019.

---

* L. Hartshorn, N. J. L. Megson, and E. Rushton: *Journal of the Society of Chemical Industry*, 1937, vol. 56, p. 266T.

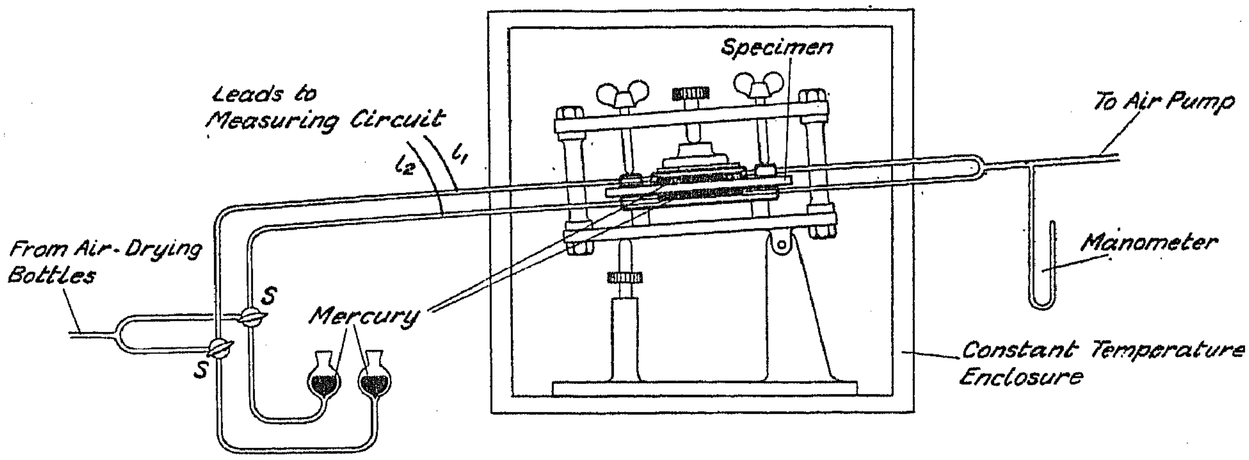


Fig. 2.—Mercury electrode-clamps: diagram showing arrangement for drying specimen.
Drying is carried out at 100° C. and at low pressure, by passing dried air slowly over the specimen. After drying has been completed, mercury is immediately introduced into electrode-clamps through 3-way cocks SS.

Resins were also prepared using various proportions of phenol and formaldehyde, from 1 to 2 mols of formaldehyde to 1 mol of phenol, but again the values were the same. It therefore becomes clear that these values are characteristic of the resin. The results suggest that the structure of the hardened resin was the same in all cases, and that only a definite proportion of formaldehyde can be taken up into combination in the formation of the hardened resin, any excess being driven off in the final heating. Thus the structure might well have been as shown in Fig. 3, for which the molecular proportions of formaldehyde to phenol approach the value 1·5 to 1 as the size of the structure is increased.

Table 1

PERMITTIVITY AND POWER FACTOR OF PHENOL, *m*-CRESOL, AND *m*-5-XYLENOL RESINS: FREQUENCY 1 000 CYCLES PER SEC., TEMPERATURE 20° C.

Resin	Permittivity		Power factor	
	Undried	Dried	Undried	Dried
Phenol-formaldehyde	4·6	4·0	0·0120	0·0083
m-cresol-formaldehyde	4·6	4·2	0·0087	0·0050
m-5-xylenol-formaldehyde	4·0	—	0·0050	—

Perhaps the most obvious way of modifying this structure is to prepare resins with *m*-cresol, and *m*-5-xylenol, instead of phenol. The resulting modifications consist in replacing hydrogen by methyl (CH_3) groups; in the case of *m*-cresol, substitution occurs at one point in each ring at positions marked * or †, while in the case of *m*-5-xylenol it takes place in the two positions * and †. When resins were prepared from these phenolic homologues and tested, the very interesting result was found that the introduction of methyl groups causes a considerable diminution of power factor under ordinary conditions, and a slight fall in dielectric constant. The actual values are given in Table 1.

It should be remarked that the resin prepared from *m*-5-xylenol was very brittle, and cracked on heating, so that it might prove to be of little practical value in spite of its lower power-factor. Nevertheless, the results are of value in showing the considerable changes in properties that can be brought about by simple changes in structure.

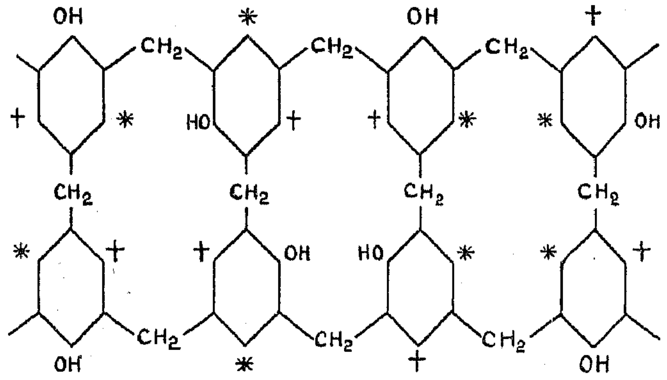


Fig. 3.—Structure of phenolic resin in hardened state. By the use of *m*-cresol or *m*-5-xylenol, methyl groups may be substituted at points marked * and †.

Moisture Content

The above-mentioned measurements were all made on resin films which had been kept under ordinary room conditions. It has already been noted that the presence of moisture in a material usually diminishes its value as an insulator, and it therefore became desirable to find out to what extent the above values were associated with moisture which the resin may have absorbed from the atmosphere. For this purpose the atmosphere of the test-enclosure was first maintained at a temperature of 20° C. and a relative humidity of 75 %, and measurements were made on resin films which were in equilibrium with this atmosphere. The mercury was then removed from the electrode clamps, a vacuum pump applied to the outlet tubes, dry air admitted to the inlet tubes, and the enclosure heated to 100° C., so that any moisture in the film would be removed. After a time the mercury was re-admitted and measurements again made at 20° C. A considerable reduction in the value of power factor was observed, and the drying process was therefore continued until the readings became constant, at which point it was assumed that all the water had been driven off. The values are given in Table 1. As previously mentioned, the heating caused the *m*-5-xylenol resin to crack, so that it could not be tested after drying. The results show that at least one-third of the power loss in the material under ordinary conditions is due to the water which it absorbs from the atmosphere. If the moisture were held as a film on the outer surface, the dielectric constant and power-factor would be expected to be different for thin and thick resin-films. Since, however, it has been shown that the dielectric properties do not vary appreciably with thickness, it follows that the moisture permeates the whole mass of the film. It will be observed that the drying also causes a diminution of dielectric constant, and from the value for the dried material, and the known value for water, it is possible to estimate the water content of any sample of which the dielectric constant is known. Thus it is estimated that the films absorb 3 % to 4 % (by volume) of water from an atmosphere of 75 % humidity. These values were afterwards checked by weighing samples which had been first dried and then stored in a suitable atmosphere (see Fig. 4, and Appendix). These values are much higher than those usually quoted for phenolic resins, but it is to be remembered that the latter are usually based on measurements made on comparatively thick specimens. It is clear from the authors' measurements that such massive specimens would take months to reach an equilibrium condition after any change in their surrounding medium, so that the results of short-period tests cannot represent the true moisture-content.

Since the water permeates the mass of the resin, the material must be regarded as possessing a more or less open structure, containing spaces through which water may pass and in which it is held. The presence of this water is also sufficient to account for the comparatively large increase of power factor produced by the addition of a little caustic soda. This material would probably be ionized by the water, and the motion of the ions in the water-containing spaces would account for the increased power-loss.

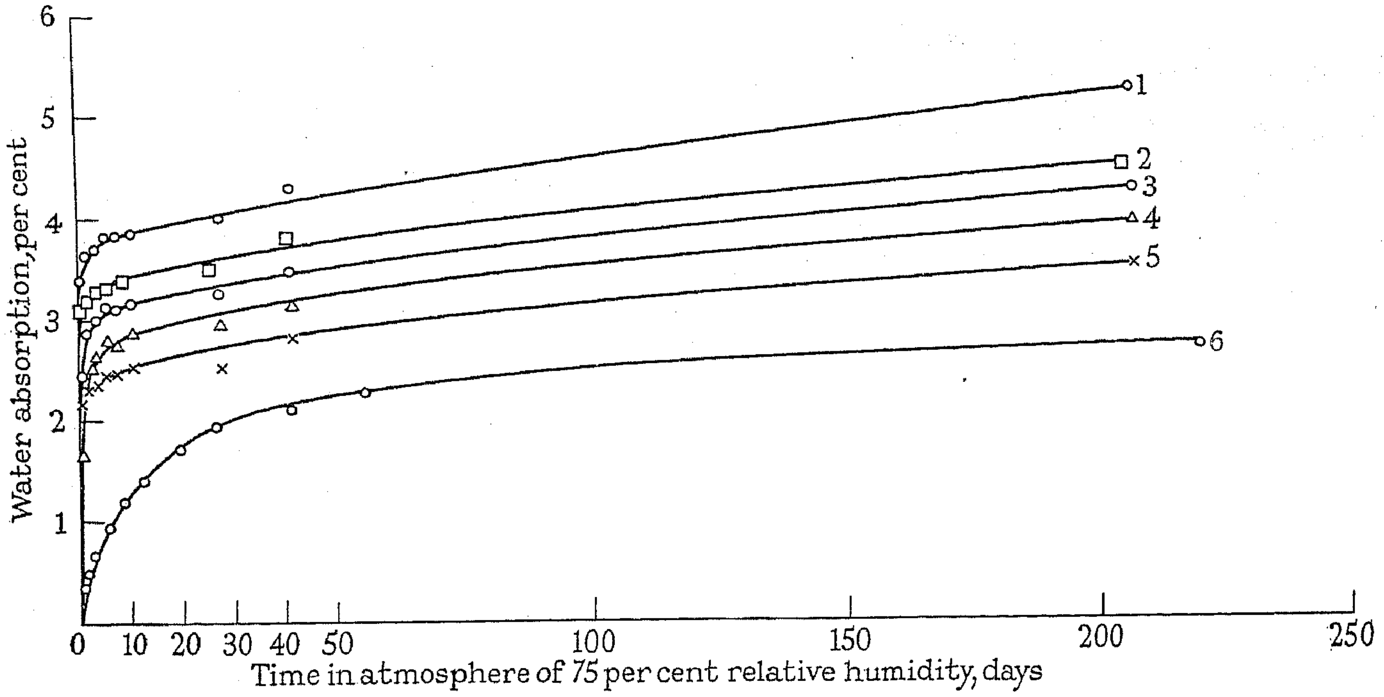


Fig. 4.—Water-absorption of phenolic resins.

No.	Catalyst	Thickness, mils.	Remarks
1	Ammonia	2·0	On foil
2	Ammonia	2·8	On foil
3	Pyridine	4·8	On foil
4	Pyridine	6·5	Detached
5	Triethylamine	2·1	On foil
6	Triethylamine	27·0	Detached

Effects of Temperature and Frequency

The variation of properties with change of temperature was determined by making measurements as the temperature of the enclosure was varied, the mercury being left in contact with the surfaces of the films, so as to prevent changes of moisture-content during the heating and cooling. The reproducibility of the results on alternately heating and cooling the samples, both slowly and rapidly, showed that the effects observed were due to changes of temperature alone and not to changes of water content. The results are shown in Fig. 5. Measurements were made at various frequencies, and the effects of change of frequency may also be seen in the Figure.

It is seen that over the range covered by the experiments the power factor of the dried resin steadily diminishes with rise of temperature; that of the undried material also diminishes with rise of temperature at high frequencies, but increases at low frequencies. This difference between dried and undried material suggests that the power loss due to the water content is of a different character from that due to the resin structure itself.

The change of dielectric constant with temperature is very small.

Resin Composites

It is instructive to consider the above results in relation to the properties of laminated boards and mouldings made with phenolic resins. As is well known, the power factors of these materials are considerably greater than those found for the pure resins, and moreover they always increase rapidly with rise of temperature. The power factor of dried paper (0·0025) is considerably less than that of the pure resin, and it is almost independent of temperature. One might therefore expect to be able to make laminated boards with a power factor of, say, 0·005 instead of at least 3 or 4 times this amount. The experiments on water-absorption show why this is not possible. The composite material consists of fragments of cellulose, etc., cemented together by thin films of resin such as we have examined. These films, as we have shown, are pervious to atmospheric moisture, which passes into the paper or wood and raises its power factor above that of the resin-film itself. These considerations emphasize the desirability of producing resins which are impermeable to water.

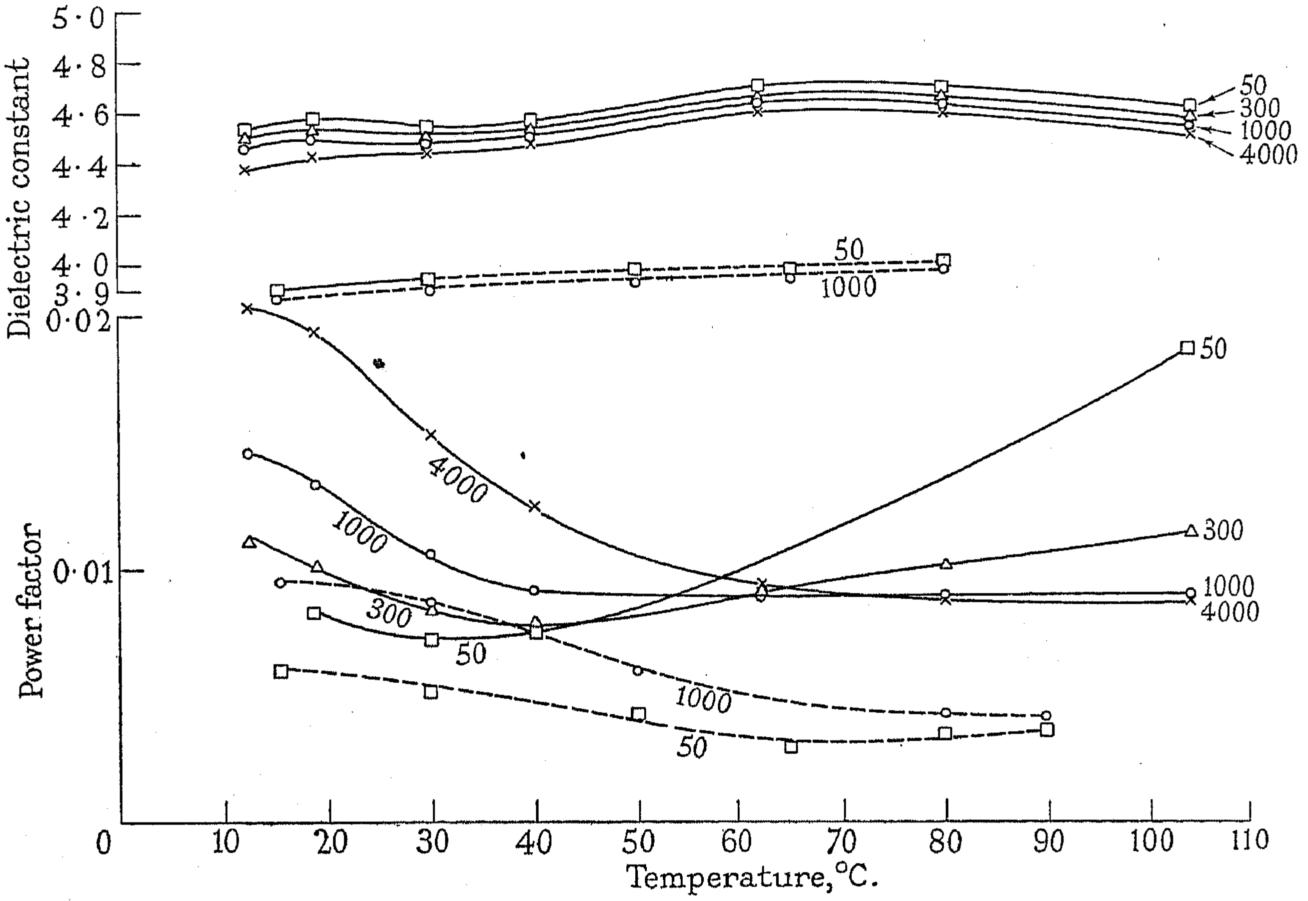


Fig. 5.—Variation of dielectric properties of phenolic resins with temperature and frequency. The number attached to each curve gives the frequency in cycles per second.

——— Sample at 75 % relative humidity.
– – – – Sample dried at 100° C.

An alternative method of tackling this problem is the use of fillers on which water exerts a less harmful effect than it does on paper. In this connection questions of cost and mechanical strength are apt to become predominant. Nevertheless, it is obvious that certain fillers might confer advantages that would be of overwhelming importance in special applications. Thus mineral fillers, which are of very low power-factor, and which are relatively little affected by water (e.g. mica and certain forms of silica), should give low power-factors and, incidentally, permanence of linear dimensions, and special heat-resisting qualities. It is interesting to note that the use of silica-gel as a filler in composite dielectrics has been described in patent literature.* The idea is apparently that silica-gel acting as a drying agent would remove the water from the other constituents. But would the water do less harm in the silica-gel than in the other materials? The authors have not been able to find any information on this point.

Conclusions: Structure

Surveying the whole of the experimental results, we see that the power factors of the hardened phenolic resins are probably characteristic of their structure, which may be roughly represented by the chemical network of Fig. 3. The OH groups distributed throughout this network are known to be strongly polar, and therefore tend to set themselves in line with any electric field that may be applied to the material. When a rapidly alternating field is applied, these polar groups will therefore tend to vibrate, and in accordance with the theories previously mentioned it is suggested that the power loss in the material is associated with this vibration.

The network shown contains no water molecules, so that the above remarks refer to the dried resin. It has been shown, however, that in an ordinary atmosphere the resins take up 3 % to 5 % of water, which means that they acquire 1 molecule of water to each 4 or 6 benzene rings, and this quantity of water increases the power factor by 50 % or more. It is not known how this water is held by the material, except that it is not by chemical forces. The large effect on the power factor produced by a little caustic soda suggests, however, that the water collects in certain spaces in the resin structure, either within the molecule or between molecular aggregates, and that the power loss associated with it is due to the motion of ions within these spaces. The fact that the additional power loss produced by the water varies in a different way with temperature from that in the dried material, is consistent with the suggestion of two different mechanisms for the two components of loss.

---

* British Patent Nos. 182422–1921 and 231781–1924.

It is interesting to consider the relation between structure and water-absorption. It has been pointed out that a polar molecule or group of atoms such as the OH group is analogous to a permanent magnet, and just as a magnet attracts iron, a polar group will attract materials of high dielectric-constant, of which water is an outstanding example. Thus materials which are of an open structure, and which contain polar groups, are likely to absorb the most water. It is therefore probable that the water-absorption of the phenolic resins is due to the OH groups in the structure. In this connection it is interesting to note that, although the addition of methyl groups to the structure greatly reduces the power factor of the dried resin, the increase of power factor due to moisture-absorption is not affected. This is quite consistent with the idea that the water-absorption is due to the OH groups, for the concentration of OH groups per unit volume of resin is clearly not greatly affected by the substitution of the methyl groups. The reduction in power factor produced by the substitution of methyl groups is more difficult of explanation. It must be remembered, however, that each polar OH group is acted upon, not only by the applied electric field, but also by the electric fields of its neighbours, and that its displacement by the applied field will therefore to some extent be controlled by the internal electric field. The presence of additional carbon and hydrogen atoms in the spaces between the polar groups would certainly modify the internal electric field, and therefore the displacement of the polar groups, and the observed reduction in power factor and permittivity probably arises in this way.

A different explanation of the decrease of power factor on the introduction of methyl groups is advanced by H. Stäger* from an examination of the properties of resins made with phenol-cresol mixtures. He suggests that *m*-cresol on condensation yields comparatively non-polar molecules of large size, and that phenol, on the other hand, forms strongly polar molecules of smaller dimensions. Stäger also finds considerable lowering of dielectric constant by the introduction of methyl groups. Unfortunately he expresses no views as to why the additional methyl groups should reduce polarity.

(6) NEW DEVELOPMENTS

Structural Units

The electrical properties of resins of one type having been studied in some detail, it is proposed to survey briefly from the same point of view the various types which have been made, noting particularly the newer developments. The need for more information about most of these materials is obvious, but what is already known, considered in relation to the general principles already outlined, suggests some ideas on future progress.

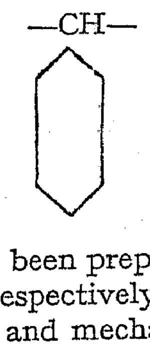
We have seen that plastics are essentially materials of which the molecules are relatively large complex structures, each molecule being built up from units of one particular kind, the size of the molecule depending on the number of units. It is to be expected that the properties of plastics will depend largely on the properties of the unit from which their molecules are built up, and it is therefore proposed to consider the various units from which plastics have already been built, and the properties of the resulting product.

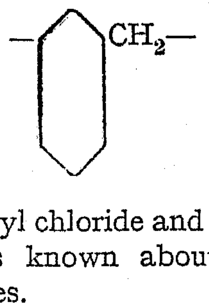
The comparatively high power-factor of the phenolic resins has been attributed to the presence of a polar OH group in the unit. This suggests that if a structure could be made similar to that shown in Fig. 3, but containing no polar groups, it would possess electrical properties superior to those of the phenolic resins. The most obvious change to make is to replace OH by H, thereby forming a hydrocarbon structure. No records of a hydrocarbon resin of this particular structure appear to exist, but several hydrocarbon resins have been made, and their electrical properties are outstandingly good. Their characteristic units are shown in Fig. 1.

Hydrocarbon Plastics

The first two of the hydrocarbon plastics shown, polystyrene and polyindene, have been made in the form of clear glass-like solids. The outstanding characteristic of these materials is their low dielectric-constant (about 2·5) and very low power-factor. Precise data are not available for both of these materials, but samples of polystyrene have given power factors as low as 0·0002, and it follows that these materials are almost ideal for work in which the minimum power-dissipation is of the first importance. Examples are cables for very high frequencies, e.g. for television, moulded components for ultra-short-wave radio work, and junctions for high-voltage cables. These two materials are apparently not yet being produced in this country.* Polyethylene has, however, recently been produced, and judging by its characteristic unit [Fig. 1(*a*)] it should have electrical properties similar to those of polystyrene and polyindene. No information is, however, available on this point.

Plastics having the following characteristic units





have also been prepared from benzyl chloride and benzyl alcohol respectively, but little is known about their electrical and mechanical properties.

The hydrocarbons also include rubber and polybutadiene, a synthetic rubber. The similarity of the characteristic units of these two materials is obvious. The units have methylene groups at both ends, and it is believed that it is the junctions of these groups which are sensitive to oxygen and which are responsible for the deterioration of these materials with age. The power factors and dielectric constants of these materials are low, but the chemical instability of the materials and the fact that they are not usually obtained in a very pure state make it difficult to give representative values.

---

* *Helvetica chimica acta*, 1931, vol. 14, p. 285.

* Since the above was written, "Distrene," a polystyrene plastic made in this country, has become commercially available.

It is to be noted that all these hydrocarbons form long chain structures. The characteristic unit functions as though it has two points of attachment only, and therefore forms linear molecules only. All these materials are thermoplastic and tend to swell or dissolve readily in liquids like benzene. Such properties appear to be characteristic of the linear molecule. We may picture the long threadlike molecules as sliding easily over one another on heating, and the solvent molecules as easily forcing the unattached threads apart. These properties may have their uses, such as the production of insulating varnishes, but for many purposes they are disadvantages. Possible means of overcoming them will be considered later.

Substituted Hydrocarbons

The substituted hydrocarbons shown in Fig. 1(*b*) are of interest in showing the kind of change which may be brought about by the substitution of an atom of Cl, O, or S for one of hydrogen. These atoms are electronegative to hydrogen, and it therefore follows that the result of the substitution is to make the distribution of electric charges within the molecule less symmetrical: in other words, the molecule acquires an electric moment, and, as we have seen, this tends to increase both the dielectric constant and the power factor. The electrical properties of these materials are therefore not so good as those of the hydrocarbons. The substitution may, however, improve the chemical properties of the materials. Thus polychloroprene and olefine-polysulphide are synthetic rubbers which, unlike natural rubber, are oil-resistant. Chlorinated rubber is more stable than natural rubber, and has alkali-resisting properties which make it of value as a coating material. The pure material has not the elastic properties of rubber, but may be obtained as a transparent thermoplastic resin, of a pale brown colour, and with good electrical properties. Mixtures of various chlorinated diphenyls may be obtained in many forms, ranging from clear liquids to glassy solids. Unlike the corresponding hydrocarbons they are not inflammable, and are therefore of value in the electrical industry as impregnating media. For this purpose the increase of dielectric constant produced by the chlorination may be an advantage.

It is to be observed that the addition of sulphur to the rubber molecule causes a profound change in the character of the unit of the structure. It has four points of attachment to neighbouring units instead of two, and the resulting molecule is not merely of the chain type, but of a kind of lattice structure in two or three dimensions. As a result of the change of structure the material loses its characteristic elastic properties and becomes much more rigid: the rubber changes to ebonite. As in previous cases, the introduction of the sulphur gives the molecule a certain polarity and tends to increase both dielectric constant and power factor, but the increased rigidity is in itself very valuable for many purposes, and no doubt contributes to the very high electric-strength, which is perhaps the most valuable electrical property of the material.

Data concerning the properties of these and other materials are collected together in Table 2. The values have been selected from published literature, which is full of inconsistencies. It is, however, believed that the values given are sufficiently representative of present-day materials to serve as an indication of the present state of the art.

Heat-hardening

The property of hardening instead of softening on the application of heat is one of considerable practical importance to both moulders and users of plastics, for it obviously tends to increase the working temperature-range of the material, to give improved mechanical properties, and also to reduce the time of the moulding operation by allowing the finished article to be removed from the mould while still hot. Such hardening is obviously likely to occur whenever the application of heat increases the size or complexity of the molecules of the material. We have seen that plastics of which the characteristic unit has only two points of attachment have molecules of the chain type. The application of heat causes an increase in the thermal vibrations of the chains, and this is not likely to lengthen them. The complexity of the molecule is therefore unaffected and the material is thermoplastic, i.e. softens on heating. It is only in plastics of which the characteristic unit has three or more points of attachment, or " active " points, that the above-mentioned property of heat-hardening or thermo-setting is to be found. Such plastics may exist in two stages: one of lower complexity in which the material is plastic and soluble in suitable solvents, and one of higher complexity formed by the linking of the simpler units into a complex three-dimensional structure, which makes the material vitreous instead of plastic, and insoluble in the usual solvents. When the structural unit has three active points we may suppose that the chain structure is the first to form, since the units at the ends of a chain have the greatest freedom and are therefore the most likely to satisfy the conditions of orientation, etc., for the linking-up of another unit. Thus the plastic condition with chain molecules is first obtained. As the temperature rises, the vibrations of the chains increase, and the additional flexibility permits linking to occur also at the active points throughout the length of the chains. The chains are assembled into a cross-linked structure in three dimensions, which is characteristic of the vitreous state of the material. The linkages, once formed, are very strong, and solvent molecules are no longer able to force their way in, and open out the structure.

It is to be noted that the heat-hardening resins have all the advantages of the plastic state when they are required, i.e. during moulding, but none of the disadvantages when they are not required, i.e. during the use of the finished product. It is therefore not surprising that they are commercially far more important than the others, although their other properties may not be so good. The characteristic units of the various resins of the heat-hardening type are shown in Fig. 6. The phenol-formaldehyde resin in the hardened state has already been considered in detail. Each CH_2 group of the structure is shared by two benzene rings. In the diagrams these groups are therefore shown cut across, to indicate that only half of each group belongs to the unit shown. In the hardened state this material is familiar to the electrical engineer as bakelite, while in the plastic state it is familiar as Novolak, used for insulating varnishes.

Table 2

PROPERTIES OF PLASTIC INSULATING MATERIALS

Material	Dielectric constant	Power factor at 10^n cycles per sec.		Resistivity		Electric strength (kV per mm.)	Softening (a) or maximum (b) temp. (° C.)	Mechanical strength		Examples
			n	Volume (ohm-cm.)	Surface (ohm)			Cross-breaking (kg. per cm²)	Impact (kg.cm.)	
Hydrocarbons										
Polystyrene	2·2–2·5	0·0004	3	10^{17}	10^{13}	40–100	70 (a)	600	2	Trolitul, Victron
Polyindene	2·4–3·5	0·0004	6	—	—	60	60 (a)	—	—	
Rubber (raw)	2·5	0·002	3	10^{15}	—	30	10 (a)	—	—	
Substituted hydrocarbons										
Vulcanized rubber (pure)	3·0	0·006 0·009	3 6	10^{16}	10^{15}	150	65 (b)	1100	50	Ebonite
Vulcanized rubber (with heavy mineral loading)	4·5	0·012 0·03	3 6	10^{14}	—	70	85 (b)	750	12	
Vulcanized rubber (silica loaded)	3·5	0·006 0·009	3 6	—	—	—	80 (b)	700	10	
Chlorinated diphenyl ..	5	0·01	3	—	—	7	—	—	—	Permitol
Heat-hardening plastics										
Phenol-formaldehyde (unfilled)	4·7	0·013	3	—	—	50–100	150 (b)	—	—	
Phenol-formaldehyde (Novolak)	3·7	0·007	3	—	—	—	70 (a)	—	—	
Phenol-formaldehyde (wood-filled)	5	0·02–0·04	3	10^{11}	10^{12}	10	150 (b)	800	2·5	Bakelite, Mouldrite
Phenol-formaldehyde (laminated paper)	5	0·03	6	10^{12}	10^{12}	10–30	150 (b)	1500	9	Bakelite, Tufnol
Urea-formaldehyde (wood-filled)	5–7	0·03–0·05	3	10^{12}	10^{12}	10	100 (b)	—	—	Beetle, Mouldrite
Urea-formaldehyde (paper-filled)	5–6	0·03–0·04	3	$>10^{12}$	10^{12}	10	100 (b)	850	3	Beetle, Mouldrite
Aniline-formaldehyde (laminated paper)	3–4	0·04	2	—	—	20	—	—	—	
Glycerol phthalate ..	5	0·01	3	—	10^{15}	—	150 (b)	—	—	Glyptal
Organic glasses										
Cellulose acetate.. ..	4–6	0·03 0·06	3 6	10^{13}	—	25–40	60 (a)	550	5	Cellomold
Cellulose nitrate ..	3–4	0·05	6	10^{11}	10^{11}	10–30	40–60 (a)	600	—	Celluloid
Methyl methacrylate ..	2·8	0·03 0·02	3 6	10^{15}	10^{14}	20	60 (a)	600	3	Diakon Perspex
Vinyl acetate	4	0·014 0·017	3 6	$>10^{14}$	—	18	50–65 (a)	—	—	Vinylite
Vinyl chloride + Vinyl acetate	3	0·015	3	$>10^{12}$	$>10^{12}$	20	50–65 (a)	—	—	Mipolam

Somewhat similar resins can be made using aniline instead of phenol (Fig. 6). Since these resins contain no OH groups, one might at first sight expect their electrical properties to be much better than those of the bakelites. However, the NH_2 group is also polar and no great superiority of electrical properties is claimed for these materials, except that the surface does not break down by tracking at high voltage.

The urea-formaldehyde resin (Fig. 6) is familiar as Beetle ware. This differs in structure very considerably from the other two resins, but appears to possess no outstanding electrical properties except that it is non-tracking. Its most distinctive feature is that it can be made colourless, and therefore can be produced in almost any desired colours. The use of a proportion of thio-urea $(NH_2)_2CS$ instead of urea $(NH_2)_2CO$ appears to improve the electrical properties.

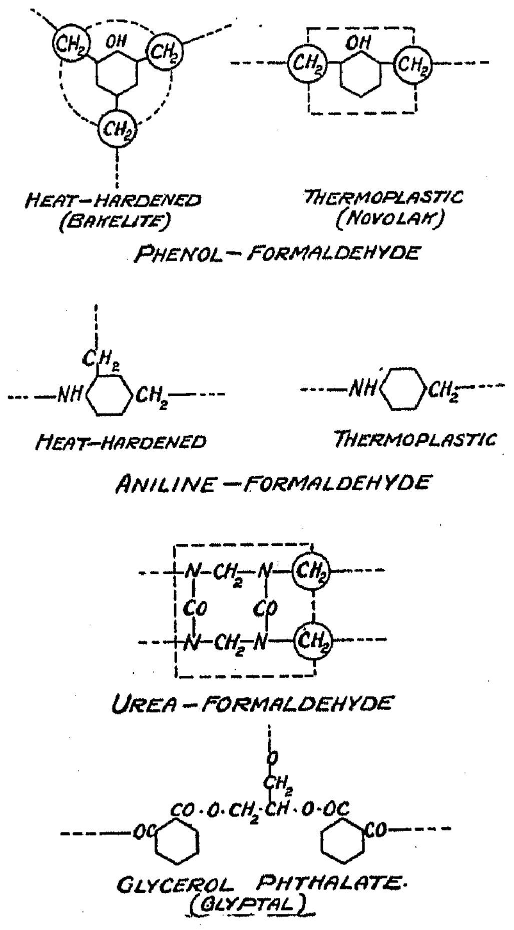


Fig. 6.—Characteristic units in the structure of heat-hardening plastics.

The last of the heat-hardening resins, shown in Fig. 6, is of quite a different type. It is obtained by the combination of glycerol and phthalic anhydride (Glyptal). It is said to be specially suitable for bonding mica (Glyptanite).

Organic Glasses

Two other classes of resins remain to be considered, the vinyl and cellulosic resins, and since they are all thermoplastic, and used more for their mechanical properties and optical transparency than for their purely electrical properties, they may be grouped together as the organic glasses. The most familiar examples are celluloid (cellulose nitrate) and cellulose acetate, while the vinyl derivatives include Perspex, a relatively new material remarkable for the excellence of its optical and mechanical properties. The characteristic units of these materials are shown in Fig. 7. Their purely electrical properties are not outstanding. The great virtue of such materials is that they provide these properties associated with other properties which are of special value in certain applications. Thus it is well known that the most valuable property of celluloid is that it provides transparent films which are very flexible, very tough, transparent, and cheap. Dangerous inflammability rules out the use of celluloid for electrical purposes, but cellulose acetate provides almost the same properties without the inflammability. Cellulose acetate (e.g. Cellomold) also combines fairly good electrical and mechanical properties with ease of injection moulding, transparency, water-resisting properties, and a high dielectric-constant. It has therefore been successfully used for the terminations of high-voltage cables. The high dielectric-constant of the material reduces the electric field in the critical part, while the other properties are all obviously necessary for the success of this particular application.

The methyl acrylic ester (Perspex and Diakon) may be roughly described as an unbreakable glass. It is more transparent than ordinary glass, and has excellent machining properties and mechanical properties generally. Its electrical properties are not sufficiently outstanding to give it many purely electrical applications, although it has obvious advantages for use as a window material in instrument work.

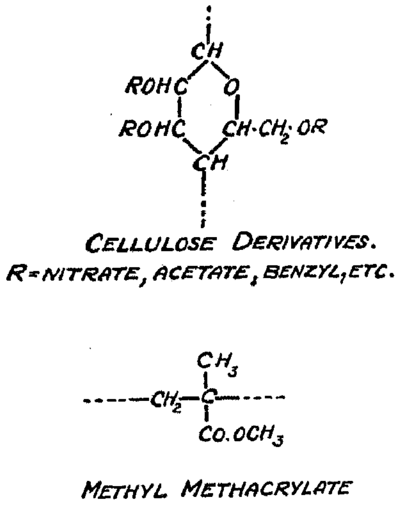


Fig. 7.—Characteristic units in the structure of organic glasses.

CONCLUSIONS

This very brief survey of existing plastics is sufficient to show that although the unit of the structure provides the key to the fundamental properties of the material, our ability to interpret behaviour and to satisfy given requirements is but rudimentary. It is of course to be remembered that the number of structural units in the molecule is also of the greatest importance, and that the mechanical properties of a material may be controlled within wide limits by this factor alone.

The polystyrenes are, for example, clear liquids when the number of units is small, changing to white powders, glassy solids, and white fibres as the number of units is increased up to, say, 10 000. The degree of uniformity of the molecules must also have a considerable effect, for a mixture of molecules of various sizes and shapes is less likely to assemble in regular crystalline formation than a collection of similar molecules. Thus the pure chlorinated diphenyls are crystalline solids of high melting-point, but mixtures of isomers such as are shown in Fig. 1 form eutectic mixtures of low melting-point. Plastic properties may also be controlled by the presence of molecules of several kinds, varying more or less in shape and in the distribution of their chemically active points. Various plastics may be mixed, or even prepared together, in order to obtain certain combinations of properties. Many materials which are too hard for some applications may be made softer or more flexible by the addition of another material, which is said to act as a plasticizer; but from our present point of view such considerations are matters of technical detail.

The ideal plastic for purposes of electrical insulation should have the electrical properties of the hydrocarbons. For the purposes of moulding it should be obtainable in a thermoplastic state, but in the finished state it should also have the mechanical properties and vitreous character corresponding to the three-dimensional cross-linked structure.

No existing material satisfies all these requirements. It has been found possible to introduce a certain amount of cross-linking between the chain molecules of polystyrene by the addition of a small proportion of *p*-divinyl benzene before polymerization. The material is then insoluble in benzene, but swells more or less according to the amount of cross-linking introduced. Thus the cross-linked structure is possible in hydrocarbons but the mechanical strength so far achieved is not equal to that of the polar materials. The following important questions arise: Are polar groups necessary in order to establish the type of cross-linking associated with great mechanical strength? If not, is it possible to find a mixture of hydrocarbon and non-polar hardening agent, which is thermoplastic at low temperatures, but which becomes hard and vitreous on the application of heat and pressure? If, on the other hand, polar forces are essential for mechanical strength, we have to find out how to control the freedom of movement of the polar groups, so as to avoid excessive energy-dissipation in the material. Our experiments suggest that this may be done by the addition of other large groups to the structure, but such questions can only be answered by further research.

Mechanical properties may also be controlled to some extent by purely physical processes, which probably have no effect on the structure of the molecule, but which control the orientation and the packing of the molecules and therefore the forces between them. Thus the stretching of a material tends to straighten out molecules of the chain type, and therefore to modify the mechanical properties of the material in certain directions. A process based on this principle has recently been patented for the production of flexible foils and threads from polystyrene, which is normally brittle. The process is one of extrusion through an orifice, and the flexibility is controlled by adjustment of the tension of withdrawal and pressure of extrusion. Such threads may have important applications in the manufacture of cables for use at very high frequencies.

It is very interesting to note that so many of the materials which have been discussed may be regarded as improvements on, or cheaper substitutes for, those natural products which were the mainstay of the electrical engineer in his earliest days. Thus the paraffin waxes possessed almost ideal electrical properties, but their thermal and mechanical properties were very poor. In polystyrene we have managed to retain the electrical properties of paraffin wax, associated with greatly improved mechanical properties. The material is still liable to soften readily on heating and to dissolve in oils, but by introducing other linkages into the structure it seems possible that these defects may be overcome. Already in styroflex we have an improvement in flexibility. Further developments in this direction hold out great promise.

Again, paper has excellent electrical properties when dry, but its affinity for water imposes great limitations on its effective use. A paper which would require no impregnation or drying would revolutionize many processes. Cellulose acetate is in some ways an attempt in this direction, imperfect, it is true, but not without promise.

Shellac has obviously many descendants, and we have many substitutes for amber, though none as yet completely successful from the electrical point of view.

Mica, however, still stands alone. It possesses most excellent electrical and thermal properties but its mechanical properties severely limit its application, and it has no plastic properties. Fused quartz has the electrical properties of mica, and some rudimentary plastic properties, but it lacks the flexibility and toughness of mica. From fused quartz we may pass, by way of a graduated series of inorganic glasses, all rather brittle, to the very tough " organic glasses," but here we have lost the electrical properties. They appear again in polystyrene, but there the thermal properties are missing and the mechanical properties are impaired. There are vast unexplored regions between mica, fused quartz, polystyrene, and our toughest plastics, but it is something to know that the insulating material we are looking for lies within and not without these known limits, and that it is a plastic.

ACKNOWLEDGMENTS

This paper is largely based on an investigation carried out at the National Physical Laboratory and the Chemical Research Laboratory for the British Electrical and Allied Industries Research Association. Thanks are due to the Association and its Director, Mr. E. B. Wedmore; to Dr. W. L. Bragg, Director, National Physical Laboratory; and to Sir Gilbert Morgan, Director, Chemical Research Laboratory; for permission to publish the paper.

APPENDIX

Water Absorption of Phenolic Resins

The dielectric constant of a mixture of two substances, e.g. an insulating material and water (or air), depends on the manner in which they are distributed throughout the material. Let κ_1 and κ_2 respectively represent the dielectric constants of the material and water (or air), and V_1/V and V_2/V respectively represent the proportions by volume of the material and of the water (or air). Assuming a random distribution of aggregates of the material in the mixture, the dielectric constant of the mixture is:—

$$\kappa_m = \kappa_1^{(V_1/V)} \quad \kappa_2^{(V_2/V)}$$

The values of κ_m for the dried and the " wet " condition are given in Table 3, and the proportion of water present (V_2/V) can be calculated on the assumption that, for the dried material, κ_2 may be represented by the dielectric constant of empty space or air (= 1), and that when the material absorbs water κ_2 has a value of 80. The values of V_2/V for the resins are given in Table 3.

Direct measurements of the water absorption of phenolic resins in the form of films were obtained by gravimetric methods. Resin films of various thicknesses up to 27·0 mils were weighed after drying at 150° C. for several hours, and then after standing for various periods at room temperature in an atmosphere of constant humidity until constant weight was obtained. The results showed that about 3 cm^3 to 4 cm^3 of water were absorbed per 100 cm^3 of resin, i.e. V_2/V was 3 % to 4 % approximately. This comparatively high value for water absorption is surprising in view of previously-published work, of which that of Leopold and Johnston[*] is typical.

Table 3

EFFECT OF MOISTURE CONTENT ON DIELECTRIC PROPERTIES OF PHENOLIC-RESIN FILMS: FREQUENCY 1 000 CYCLES PER SEC., TEMPERATURE 20° C.

Resin	Thickness (cm.)	Before drying		After drying		$\frac{V_2}{V}$ (per cent)
		Dielectric constant	Power factor	Dielectric constant	Power factor	
Phenol-formaldehyde ..	0·006	$4\cdot8_7$	0·0113	$4\cdot1_2$	0·0071	3·8
	0·0051	4·5	0·0130	$3\cdot8_5$	0·0095	3·6
m-cresol-formaldehyde ..	0·0075	$4\cdot8_1$	0·0086	4·1	0·0049	3·3

The apparent discrepancy is to be attributed to the fact that most published determinations refer to the water absorption of comparatively massive pieces of resin, so that minor surface effects become negligible when expressed in terms of total volume. Recent work,[†] published since these measurements were made, confirms the high water-absorption of films.

The authors' own observations are summarized in Fig. 4. The curves were obtained by plotting percentage increase in weight against time of standing in an enclosure kept at a relative humidity of 75 %. Samples were exposed to this treatment in the form either of films on copper foil (when the total thickness of resin on both sides of the foil was measured) or of detached films of resin. Resins made with pyridine, ammonia, or triethylamine catalysts were tested, and various thicknesses of film were examined.

Two main deductions can be made from these curves:—

(1) For resins made with the same catalyst, the rate of water absorption is approximately inversely proportional to thickness of film.

(2) Absorption does not appear to reach a maximum, at any rate after 220 days, but to increase slowly in a linear manner with time, following a rapid initial absorption which is approximately of the form $t = aA^n$, where t = time, A = percentage absorption, and a and n are constants, such that n is nearly constant for the whole series.

It is difficult to assess the effect of catalysts, since it is not certain that other factors, involving the manner and extent of adhesion of films to the copper foil, may not be masking their influence.

It will be seen that there is good agreement between the values of water absorption measured directly and those calculated from the electrical measurements on the assumption of a random arrangement of aggregates of resin in the films. It therefore seems probable that the aggregates are distributed in this manner, and that the water permeates the material and occupies the spaces between adjacent aggregates. The high water-absorption of the resins suggests that the spaces between aggregates must be comparatively large.

[The discussion on this paper will be found on page 488.]

---

[*] *Journal of Physical Chemistry*, 1928, vol. 32, p. 876.

[†] G. M. KLINE: *Bureau of Standards Journal of Research*, 1937, vol. 18, p. 235; also R. L. TAYLOR, D. B. HERMANN, and A. R. KEMP: *Industrial and Engineering Chemistry*, 1936, vol. 28, p. 1255.

DISCUSSION AT A JOINT MEETING OF THE INSTITUTION AND THE PLASTICS GROUP OF THE SOCIETY OF CHEMICAL INDUSTRY 24TH MARCH, 1938

Mr. H. Langwell: If the physicist and the engineer will state what they consider to be desirable qualities in plastics, the chemist will tell them what qualities it is possible to provide; somewhere between these two limits lie the improvements and the broad lines of research which the chemist is trying to find at present.

Plastics chemists have been surprised at the great interest which the electrical industry in general has taken in some of their new products. It is interesting to recall that one of our pioneers, Dr. Baekeland, started his researches into phenolic plastics because he wanted to improve on natural shellac, which electrical engineers have used for a long time and which has very obvious defects in addition to its advantages.

Until quite recently, the chemist has usually worked in the field of crystallizable products. Unfortunately, Nature does not abound in crystalline materials, but tends to produce large colloidal molecules. An interesting fact is that Nature tends to produce straight-chain polymers with inherent fibrous structure: e.g. a single fibre of a soft material like cellulose is about as strong as steel. Rubber is another natural product of the straight-chain polymer type: its great flexibility is its outstanding property. Cellulose has the disability of absorbing water and becoming practically useless as a dielectric, while rubber has a tendency to perish. Even vulcanite may suffer a surface deterioration which renders it useless in time.

A type of polymer which Nature does not produce in abundance, but in which the electrical engineer has a keen interest, is the saturated hydrocarbon polymer. The advantage of the hydrocarbons is that they are very inactive chemically; they are non-polar—which is saying the same thing in another way—and they have extraordinarily low power-losses. Nowadays, when the voltages and frequencies employed in industry are increasing, the question of power factor is of great importance. Concurrently the chemist is beginning to understand how to make hydrocarbon polymers: he has to start out with something which is not inert, otherwise it will not polymerize, and so he starts with a reactive unsaturated hydrocarbon and polymerizes it until he ends with what is in effect a saturated hydrocarbon, e.g. polystyrene.

Speaking generally, the inorganic, mineral insulators have poor moulding properties in comparison with the organic plastics.

An interesting feature of these hydrocarbon polymers is their extraordinary resistance to water, in which respect they are similar to paraffin wax and sulphur. To all intents and purposes they are not affected by water, and their electrical properties remain practically unchanged by it.

Have the authors considered the possibility of accelerating the polymerization of monomeric styrene so that the product could be used for impregnation? It is an ideal material, but as soon as its molecular weight is raised in order to confer mechanical strength it is very difficult to impregnate porous materials with it.

Mr. A. R. Dunton: The authors, when dealing with moisture penetration, confirm the fact that water permeates the mass of the resin, which must be regarded as a more or less open structure containing spaces through which water may pass. Actual experience of dealing with condenser bushings made up of a laminated structure and protected by a resin surface offers a confirmation of this. It may be of interest to note that this surface network can be effectively closed by filling the spaces with an inert filler so as to prevent effectually the passage of moisture.

Under the heading " Resin Composites," on page 481, it is stated that the power factor of dried paper is 0·0025, but when making a study of this nature it should be borne in mind that the power factor of papers with the same degree of dryness is influenced by the type of fibre employed in manufacture. For instance, a paper made from a kraft paper base may have a power factor of 0·0056, which may be possibly increased to a figure of 0·0063 when a mixture of cotton and chemical wood pulp is employed.

It is recognized that laminated-paper products in which paper predominates possess lower power-factor figures than similar products with a higher resin-content. This is borne out by the fact that synthetic-resin varnish-paper boards of the tropical variety, recognized by B.S.S. No. 547—1934, when tested at 90° C. have power-factor figures sometimes many times in excess of 0·150, whereas the general-purpose variety of board, manufactured in accordance with B.S.S. No. 316—1929, will generally possess a power factor of about one-third this figure.

Although in these two cases the electrical breakdown values may bear some relationship to the power-factor figures, there is apparently no direct connection between power-factor observations and electrical minute values, unless only one type of product from a given concern is dealt with at a time. This apparently suggests that every different maker has a combination of power-factor figures and breakdown values which are only true for that particular product.

Towards the end of the paper some interesting references are made to various plastic materials; from an electrical point of view the polystyrene products seem to offer the best features, with low-power-factor figures of 0·0002. Unfortunately there appears to be some difficulty in utilizing these materials when made into definite mouldings, owing to the possible formation of fissures or cracks. It is understood, however, that some of these imperfections are overcome by the production of this type of material with a molecular weight exceeding 30 000 so as to eliminate brittleness.

Among the materials mentioned in Table 2 is a non-inflammable plastic referred to as chlorinated diphenyl, which it may be assumed is the same material as the G.E.C. Pyranol made in America. It would be of interest if the authors could give some information regarding actual mouldings which are being made from this base.

Paraffin wax is mentioned on page 486 as possessing almost ideal electrical properties; but it should be borne in mind that since moisture can readily penetrate into and through paraffin wax this material is not ideal for impregnation purposes.

Mr. H. V. Potter: The authors' model of the structure of bakelite resin is a convenient way of explaining how certain phenomena take place, but I do not believe it gives a correct picture of the physical structure of this material.

On page 476 the authors refer to the difference between the behaviour of a crystalline structure and that of a plastic when heat is applied, and they conclude that the plastic condition occurs when the molecules of the material are not all exactly similar. The following example confirms that theory. In my early days of experimentation on these materials, I succeeded in dissolving out and reasonably purifying a product of the phenol-formaldehyde reaction. It was a white granular material: I did not crystallize it—but it was certainly not plastic. I succeeded in converting it back into a plastic resinous body by merely melting it again with about 5 % of phenol.

With regard to Section (5) of the paper, since all alcohol contains water, was it wise to use an alcoholic solution of the resin in order to obtain a film which was afterwards used for tests on absorption of moisture? The presence of moisture from the solvent may account for the variations which the authors found among samples prepared on different occasions.

They regard the polar OH group as being responsible for some of the electrical features of the phenol-formaldehyde materials and for their water-absorption properties. I would point out to them that the urea-formaldehyde materials, which have a much higher water-absorption, do not contain polar OH groups. Mr. Dunton referred to paraffin wax, pointing out that it has a porous surface into which water may penetrate; paraffin wax again has no polar OH group, as far as I understand it.

I do not follow the authors' arguments on page 480 with regard to water absorption, which they say must be an absorption below the surface and not a surface film, because the dielectric constant does not vary with thickness. It seems to me that the reverse must be the case. Further, the figures which they give of 3 % to 4 % absorption of water do not represent the absorptions which are obtained on commercial materials such as mouldings or laminated products, produced under conditions of high temperature and pressure. The authors question some figures which they say are the ones usually quoted for phenolic resins, and I should like to ask them to what figures they are here referring.

With regard to Fig. 5, what is the significance of the undulations in the curve representing the dielectric constants?

Mr. G. H. Gardner: Hitherto if one wished to change the properties of a resin one experimented with the process of manufacture, and possibly after a series of trials achieved the desired effect. Certain resins, such as the phenolic heat-hardening ones, have been found suitable for electrical insulation. I understand that a knowledge of the molecular structure now enables chemists to predetermine certain physical properties of the resin, and I should like to ask the authors whether they consider it is likely to become possible to forecast, for instance, the effect upon the electrical properties of a cresol-formaldehyde resin of a change in the cresol " fraction " used.

I am keenly interested in any improvements which are likely to be achieved in resins, particularly as regards the dielectric properties. I regard a low power-factor combined with a reasonably low dielectric-constant as of much more importance than a high breakdown strength, since the former govern the most important property of an insulator, namely its permanence in service. Do the authors suggest that lower power-factors than those available at present are unlikely to be obtained from heat-hardening resins, and that one must look to the thermoplastics for progress in this direction? Heat-hardening resins are peculiarly suitable for the manufacture of bushing insulators and the like, and, for a thermoplastic resin to find successful application in this branch of the plastics industry, its initial softening-point must be so high that changes in physical and electrical properties associated with plasticity do not occur below 100° C.

Finally, I should like to put forward, for the consideration of the chemists and their future research, what I consider to be the properties of an ideal resin for the manufacture of high-voltage laminated-paper bushing insulators. Briefly, they are as follows: (1) The resin must be capable of being coated upon a paper web with ease, preferably by solution in a cheap solvent which can afterwards be completely removed without difficulty. (2) When the resin-coated paper is softened by heat and two paper surfaces are rolled into contact, firm adhesion should result. I attach great importance to the adhesive properties of the resin. (3) The resin should preferably, but not necessarily, be heat-hardening. If we must go to the thermoplastics for low power-factors, no softening of the resin composite should take place below 100° C., and no volatiles should be emitted during the processing. (4) The electric strength should be high, say 90 kV per mm., and the power factor low, say 0·005 at 20° C. There should be as little increase as possible in power factor with increase in temperature up to at least 90° C. (5) The resin should be impervious to water. (6) Its mechanical strength is not necessarily important, since this property is provided by the paper base. (7) The resin must be permanent in all its properties. There must be no alteration in electrical or physical properties with time or continued subjection to electrical stresses.

Mr. R. I. Martin: I should like to raise an objection to the term " plastics." The authors state: " The most characteristic property of plastics is that by suitable treatment they may be made to pass through a plastic condition." It should, however, be borne in mind that, in their final condition, the materials with which we are concerned are not usually plastic. There is a danger that engineers may look with a certain contempt on materials which are called plastics, because they are generally looking for materials which have good elasticity. I think that this situation has arisen from the fact that chemists tend to look upon these materials from the point of view of a raw material from which something else is made, whereas the engineer is primarily concerned with the properties of the finished product. I prefer the terms " moulded composite " or " moulded material " to the term " plastic," as these refer to the principal manufacturing process, in the same way that engineers know cast iron and forged steel; incidentally, these both pass through a plastic stage during manufacture.

It is a pity that the authors' experiments were carried out on films of the order of only 2 to 7 mils thick, as, in practice, synthetic-resin films are very seldom used alone; they are generally employed in combination with some other material. Under the conditions of moulding of synthetic-resin materials, there is usually a fairly large bulk of material, of a thickness from $\frac{1}{16}$ in. to 1 in.; the material is enclosed in a mould, and the time of moulding and heating is usually quite short. In the authors' experiments, however, the films were applied in several coatings, each being very thoroughly baked. Whilst I appreciate the great importance of dealing with a resin as a resin, and determining its characteristic fundamental properties, I consider it would be of great help if research could, in the future, proceed on the lines of dealing with a larger bulk of material under conditions similar to those in which it is used. This point is emphasized by the curves in Fig. A showing the relationship between power-factor and temperature which we obtained on a synthetic-resin disc about $\frac{1}{8}$ in. thick. They indicate that in the condition in which this material is normally obtained from the mould there is a very rapid increase of power factor with temperature, which is generally considered to be (and is) a bad thing; but after further baking there is a considerable improvement.

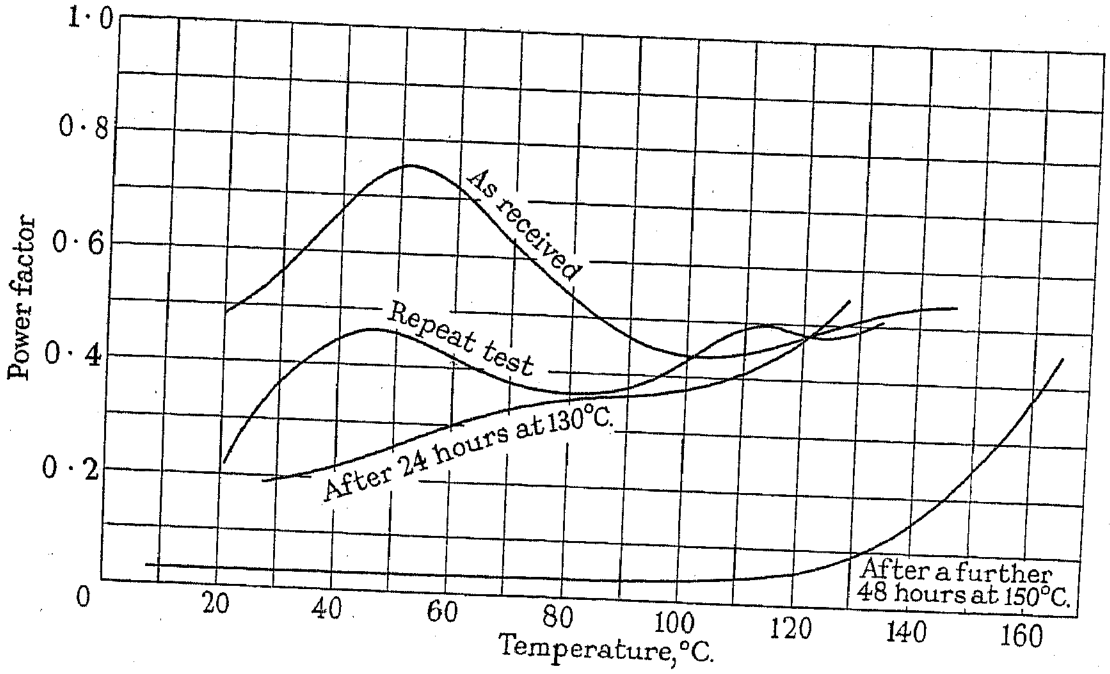


Fig. A.—Power-factor/temperature test on moulded phenol-formaldehyde synthetic resin disc.

Dr. L. A. Jordan: It has been shown that the factors which affect or determine insulating properties are the type and structure of the molecules, their mobility or immobility, and the presence of impurities, notably entrapped water. Furthermore, in the final plastic product the role of the filler must not be forgotten.

The great problem of resin chemistry seems to be to avoid the molecularly porous structure, and I suggest that similar considerations apply to both mechanical structure and electrical properties. These matters involve the log-jam concepts of Kienle, and Houwink's *lockerstellen* idea. Primary chemical linkages are sufficient to explain most things about the formation and structure of resins, and, with the aid of Kienle's third postulate (namely that the relative size and shape of the reacting molecules and the position of the reacting points largely determine the physical properties of the polymeride), offer some explanation of the physical properties observed, except the low value, relative to the theoretical figures, of the mechanical strength. To meet this difficulty the *lockerstellen* idea has been introduced.

The classical work of Joffe on rock-salt crystals is a direct parallel. He showed that the actual tensile strength of single crystals of rock salt was considerably less than the theoretical value calculated from electrostatic cohesion theories, and suggested that the explanation of this was that crevices penetrated from the surface of the crystal into the interior. When the crystal was immersed in hot water so that the surface was continually dissolved away, thus preventing the formation and growth of crevices under strain, the tensile strength was found to be greatly increased, actually to within 80 % of the theoretical value.

Much might be learned about the fine-structure of resins by polymerization experiments with thin films, preferably monomolecular films, in which the reacting molecules are relatively free to move, as, for instance, on a mercury or water surface. It might be possible in this way to determine the exact role of the OH groups in phenolic resins, since ionization and ionic movement is possible. At the moment, however, insufficient defined experimental work has been carried out on the simpler substituted phenols.

Prof. Willis Jackson: The authors refer very frequently to the orientation of polar groups as a cause of dielectric loss, but unfortunately do not discuss the nature of the underlying physical mechanism. With liquids one can think fairly straightforwardly in terms of a measurable coefficient of viscosity, but it is not easy to visualize the corresponding internal physical parameter for solids. Measurements on solutions of long-chain esters in solid paraffin-waxes have suggested that the "apparent internal viscosity" of the crystalline wax to dipole orientation within it is of the same order as the room-temperature viscosity coefficient of castor oil. This is difficult to understand physically, but is a very important consideration since it is the internal viscosity, linked with the dimensions of the orienting polar groups, which determines the region, in temperature and frequency, within which particular groups become responsible for appreciable dielectric-loss. Thus, referring to Fig. 3, it is very important that we should know more about the nature of the motion which the OH groups undergo under the applied electric field and of the viscous forces which they encounter in the process of orienting, since these are fundamental factors affecting the electrical characteristics of the material concerned. While the study of the phenol-formaldehyde resins is of great practical interest and importance, their complexity of constitution makes them a somewhat unsuitable channel for the clarification of these fundamental issues, and it is to be hoped that the authors will carry out supplementary measurements on materials of simpler and more definable chemical composition.

The statement that the power factor of the experimental bakelite resins was unaffected by the addition of a small percentage of hexamine "impurity," and on variation of the phenol and formaldehyde proportions in the starting mixture, should, I feel, have been supported by measurements extending over a wider range of frequency than that employed. The need for more extended measurements is also apparent in the statement on page 482 concerning the effect of introducing methyl groups into the bakelite molecule, since while it is certainly not possible on the experimental evidence given to decide whether the observed reduction in power factor is due to a reduction in the dipole moment of the OH groups or to a change in their relaxation time imposed by the change in environment, this decision could probably be made were it to prove possible to determine in both cases the position and height of the power-factor maximum associated with the orientation of these OH groups. This is the sort of point which it is very important to have clarified.

On page 482 the authors refer to the absence of data on the new material polyethylene. A limited series of measurements which I have been able to carry out recently on a sample of this material has shown that its power factor, both at low and at high frequencies, is comparable with, though somewhat higher than, that of polystyrene. It differs appreciably from polystyrene, however, in its physical and mechanical properties, and this raises a very important issue, namely that whereas from the known constitution of the monomer and our present knowledge of the factors governing electrical behaviour it is possible to infer correctly that the polymer of such materials, when produced, will have excellent electrical properties, we are not in a position as yet to forecast the probable physical and mechanical properties. Since it is these latter properties which usually determine the applicability of materials to purposes for which they are ideally suited electrically, it would seem desirable to direct dielectric research towards the study of these properties much more definitely than is at present the case. An understanding of the mechanisms underlying the mechanical strength, hardness, elasticity, plasticity, resistance to moisture absorption and penetration, etc., of dielectric materials is just as important as of those governing their purely electrical properties; yet whereas the techniques of electrical measurement are now well developed and are being widely applied to the study of materials, equally scientific techniques for investigating the above physical and mechanical properties are either not yet available or, where available, do not appear to receive the systematic application which their significance and importance warrant.

Mr. W. J. Brown: In the section dealing with resin composites (page 481) the authors say that since cresol-formaldehyde resins have a power factor of approximately 0·005, and since paper has a power factor considerably smaller than this, one might expect to make laminated sheets to have a power factor of about 0·005. Actually, power factors of 3 or 4 times this amount are measured in practice, a fact which the authors attribute to the presence of water. I believe, however, that the high power-factors of laminated synthetic-resin-paper sheets are due to the presence of phenolic compounds. Cylinders and condenser-bushing insulators made from exactly the same materials do in fact have power factors of 0·005 and less. Let us consider the methods of manufacture employed. Both the sheets and the cylindrical insulators are made from resin-coated paper, but for the former the paper is cut into separate sheets, which are stacked one above the other, put into a press, and consolidated under heat and pressure; whereas in the case of the cylinders and condenser-bushing insulators a continuous paper web is carried over heated rollers, and the paper is not rolled into contact with its mating face until the process of polymerization has been almost completed. If one heats a synthetic resin of the cresol-formaldehyde type until it is completely polymerized there is a loss of weight of about 20 %: about 4 % is due to water, and the rest, I presume, is due to phenolic compounds. If the emitted vapour is caught and condensed, light feathery crystals result which liquefy on heating. In the manufacture of sheets, these phenolic vapours cannot escape and they therefore become an integral part of the product; in the case of the cylindrical insulator, however, they escape whilst the paper is going over the heated rollers, and the final product has not these emitted vapours. I believe that the difference between the power factor of a condenser bushing insulator and that of a corresponding sheet made of the same material is due to the presence of these vapours. Chemists will confer a great benefit on insulation engineers if they will synthesize a resin which emits no vapours during the process of polymerization.

Table 2, which gives the properties of specific insulation materials, quotes the power factors at different frequencies, ranging from 100 to 10^6 cycles per sec. Now, resin-composite materials do in fact have different power-factors at different frequencies, and there are many insulating materials which have high power-factors at 50 cycles per sec. and very low ones at 1 000 000 cycles per sec. It seems essential that the tests should be made at the frequency at which the insulating material is going to be used, and in the vast majority of cases this means dielectric-loss measurements at 50 cycles per sec.

Dr. A. E. W. Austen: I wish to make a few observations with regard to Table 2, and the electric strengths given therein. No mention appears to be made of the method of test used in obtaining these values. The apparent electric strength varies over quite wide limits with thickness, the nature of the electrodes, the time of application of voltage, and, above all, the nature of the ambient medium: cellulose acetate, for instance, can be subjected to a stress 8 times higher than the value given in the Table. Electric-strength figures are therefore of little value without careful definition of the conditions under which the measurement was made.

The magnitudes of these electric strengths would seem to suggest that a commercial test was used in which discharges in the surrounding medium (air, perhaps) were not suppressed. When high-grade dielectrics are tested under these conditions, the ambient medium generally breaks down before the dielectric, and the breakdown of the test dielectric generally then ensues as the result of chemical or physical effects of the discharge, and also possibly owing to the application of the subsidiary point electrode to which the impinging end of the discharge approximates, with corresponding concentration of stress. The electric strength so measured therefore depends on a number of properties—such as dielectric constants, resistivities, surface resistivity, and resistance to chemical action—as well as on the true electric strength of the material. Provided the ambient medium (if any) can be so chosen that it is without chemical or physical action on the dielectric, and does not break down, the value obtained is the intrinsic electric strength of the material. In the case of certain dielectrics, polar crystals, for example, it is probable that this intrinsic strength can be calculated from the other physical properties of the material.

While apparent electric-strengths are useful in comparing similar dielectrics, and also afford a basis of engineering design in some cases, it is felt that where, as in this case, an attempt is being made to correlate the electrical properties of a body with its chemical structure and composition, the intrinsic electric-strength would be a more relevant quantity.

Dr. J. O. Cutter: I shall confine my remarks to one point, namely the fossil resins.

Amber is the oldest of all the fossil resins, and probably the one in which the acid value is lowest. Ageing of a fossil resin decreases the acid value, i.e. polar acidic groups disappear, and are lowest in the oldest of the fossil resins. This suggests that experiments should be made upon the artificial ageing of a phenolic resin or other condensation-type resin, in order to decrease the occluded water and to cause the disappearance of polar groups, with which the authors associate poor electrical properties.

Mr. J. H. Bennitt: It would be interesting to know whether if we took a film of polystyrene resin (which is usually conceded to have negligible water absorption) and deposited it from solution in a manner analogous to that used for making the resin films referred to on page 478, it would indeed in similar tests give water-absorption and change in dielectric properties of a negligibly small amount.

The authors found that whatever proportion of formaldehyde they used in making resins, the products all had the same electrical properties. They say that this suggests that " the structure of the hardened resin was the same in all cases." As just previously they had found that they could add hexamine or phenol to the resin with little effect, I do not quite see why they could not imagine their resins to contain different proportions of combined formaldehyde, again without this having much effect on the electrical properties. I do not quarrel with their formula for the structure of the resin, but am uncertain that these results support it.

I suspect that the vapour which Mr. Brown mentioned as being trapped when laminated boards are pressed up, is water vapour itself. This is formed during the heat-hardening condensation and trapped in the board. The production of a heat-hardening phenolic-type resin with admirable electrical properties, but producing no water whatever during the hardening process, would be a great step forward. A good deal has been done along these lines, and such boards are available commercially down to a power factor of 0·015 at 800 cycles per sec.

Mr. W. E. Pattman: The point which I wish to make arises out of Mr. Dunton's observation that greatly improved power-factor values were obtained when a filler was used in the synthetic-resin varnish employed as the surface coating of a bushing. This seems to indicate that the spaces to which the authors refer are not so small as has been suggested. Do not the authors consider that the effects described in the paper would be altered to a great extent if the films were produced under pressure?

I quite realize the difficulty of carrying out the suggestion which has been made of working with considerable masses of material, because, as the authors show, the time required to obtain equilibrium is very long even in the case of thin films. If the thickness were increased to a considerable extent the time required for making the tests would become impossibly long.

Have the authors considered extending their work so as to make it applicable to the conditions which occur in practice? In the great majority of cases, these resins are used in the form of plastics which are moulded rather than used as films, and it is not easy to produce perfect films from such resinous materials.

Mr. E. B. Moullin: The first point I wish to raise is in relation to moisture content, mentioned on pages 480 and 481. The power factor due to a given amount of moisture depends enormously on the shape of the microscopic droplets of water.* Water is vastly less harmful if it is in the form of spherical droplets than if it is in the form of long threads (I am not referring here to cavities large enough to be perceived by a moderate-power microscope). If silica-gel, referred to on page 481, possesses the property of drawing the water into it and holding it in minute spherical droplets, then the water will do less harm than when it is dispersed elsewhere in threads. Even if silica-gel does not have this property, there may exist some other substance which has, and I think the use of such a substance, if it could be found, would be very beneficial: this may suggest a useful line of attack.

To my mind, one of the outstanding problems at the moment is to explain why in Fig. 5 the power factor changes so little with the temperature: the range is only about 2 to 1, whereas other experiments would lead one to expect a change of perhaps 100 to 1. But of this later.

---

* See R. W. SILLARS: *Journal I.E.E.* 1937, vol. 80, p. 378.

Though the authors wisely state that the figures in Table 2 must not be taken too literally, yet I think the figures for chlorinated diphenyl (Permitol) are misleading and merit a special note in the paper. The dielectric behaviour of this material is quite different from that of any other on the list: for its power factor changes some fiftyfold in a temperature range of about 30 deg. C. This is well illustrated by Fig. B, showing results obtained by Prof. W. Jackson in the days when he was working with me in Oxford. The power-factor/temperature curve is shaped like a resonance curve, and the position of the maximum depends on the frequency. This curve indicates how misleading it is to quote one figure for Permitol in Table 2. (In saying this I am not concerned because the reader is given a wrong value, but because he has not had his attention drawn to a behaviour which is very unlike any mentioned in the paper.) Fig. 5 is in striking contrast, for there the power-factor range is only about 2 to 1 in 100 deg. C. It is not difficult to understand the behaviour of Permitol, and the curves in Fig. B can be predicted from viscosity measurements alone, without any electrical measurements. The behaviour of Permitol is not unique; it is typical of many dielectrics we have made in Oxford, including polystyrene loaded with polar impurities.

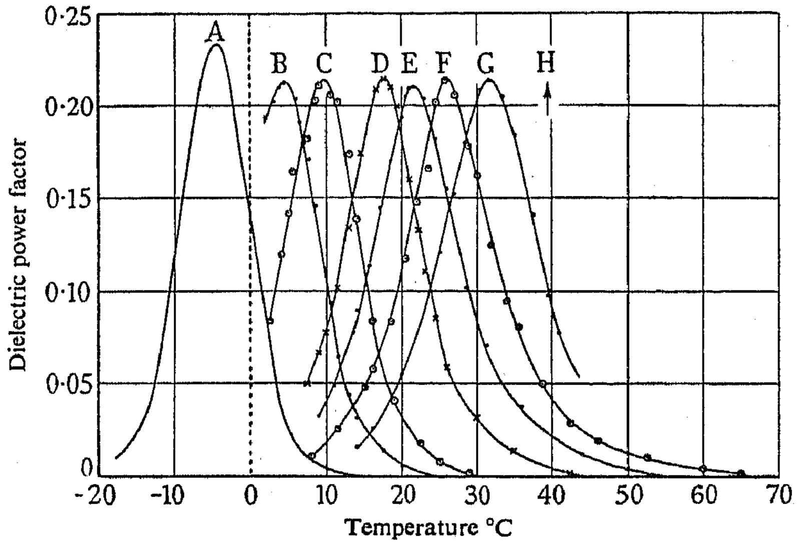


Fig. B

Frequency values (cycles per sec.): A, 50; B, 10^3; C, 6×10^3; D, 10^5; E, $2{\cdot}95 \times 10^5$; F, $9{\cdot}5 \times 10^5$; G, $2{\cdot}75 \times 10^6$; H, $1{\cdot}09 \times 10^7$.

In my view Permitol typifies the behaviour of a normal dielectric, and I regard the behaviour of phenolic resins, ebonites, etc., as abnormal and anomalous. That the majority of commercial dielectrics are anomalous does not, in my opinion, make this attitude absurd. I suggest that one of the most important problems to-day is to find the reason why phenolic resins do not behave like Permitol. For its behaviour is much more satisfactory to the technician, since a few degrees' change of temperature can always result in good dielectric properties of a material inherently capable of very bad properties. It is easy to understand why the power-factor/temperature curve should have a sharp peak, and I know of no clue to the reason why this does not occur with ebonites and bakelites. Surely Fig. B, relating to Permitol, is full of hope and promise for better materials. It shows that molecules are capable of behaving in a way which is favourable to the electrician, and moreover in the way which our understanding of them would suggest. Let us find out what inhibits this behaviour in phenolic resins, and then we may be able to remove the inhibition and obtain much better materials.

I would now suggest to the plastics chemists who are with us that they would help us very much by attacking seriously the relation between mechanical properties and the content of polar groups. I feel that the limitations of mechanical properties are in fact greater than the limitations of electrical properties. So far as I know, all insulators have deplorable mechanical properties compared with common metals. I suggest that we electricians regard it as inevitable that an insulator must be abominable stuff mechanically, and fatalistically take the world as we have found it, without very much prospecting. It seems possible that the physical chemists could produce organic compounds which are much better mechanically than those we know at present. Polar groups have considerable powers of increasing the Van der Waals forces and thereby increasing the strength and raising the melting point. I ask the plastics chemists to investigate this and to disregard the fact that polar groups can produce a bad power-factor: it should be noted that I say *can*, and not *must*. When we have learned how to use polar groups to rivet our structure together I think we shall also have learned how to make the rivets tight enough not to rattle about at ordinary temperatures, or else to use them as nicely-lubricated pin joints.

Mr. S. W. Messent (*communicated*): At the present time the engineer concerned with insulation for use at power frequencies is primarily interested in resins of the phenol and cresol-formaldehyde type. One disadvantage of these is the formation of water during the chemical reaction which takes place in their synthesis, and if the chemist could produce a resin of the same general characteristics in which this evolution of water were absent I have no doubt that a considerable advance would be made.

I should appreciate the authors' explanation of the general decrease in power factor with rising temperature shown in Fig. 5. This applies particularly to the sample dried at 100° C.

Referring to Table 2, an aniline-formaldehyde product which is commercially available is " Panilax." This has the properties shown in Table A. Many of the figures in Table 2 have little significance unless the conditions of test are specified. The electric-strength figures quoted in Table A for " Panilax " are the 1-minute breakdown stresses at 90° C., the test specimen being 1·5 mm. thick for the bonded-paper material and 1 mm. thick for the resin. The impact test results were obtained on samples 6 mm. square; with materials of this class, comparisons are only possible between samples of the same cross-section.

Mr. R. W. Sillars (*communicated*): The long-standing popularity of phenolic resins as moulding materials has naturally led to a great deal of work being done on their electrical properties, but perhaps it may be emphasized again that from a purely electrical point of view they are among the least attractive of materials. The water produced during the reactions of the curing process may escape to an appreciable extent from the thin films used in the authors' experiments, but cannot be properly

Table A

		" Panilax " bonded paper	Moulded " Panilax " resin
Dielectric constant		3·5	3·5
Power factor		0·015–0·03, $n = 2$	0·003–0·01, $n = 2$
		0·004–0·006, $n = 6$	0·004, $n = 6$
Resistivity	Volume (ohm-cm.)	10^{12}	$>10^{15}$
	Surface (ohm)	10^{12}	$>10^{14}$
Electric strength (kV per mm.)		30	27
Maximum temperature, °C.		100	80
Mechanical strength	Cross-breaking (kg. per cm.^{2})	1 700	1 100
	Impact (kg. cm.)	7	4

expelled from bakelite as normally used and will probably remain, partly as separate loosely-bound molecules, partly collected in small pockets in the microscopic crevices in the material.

Isolated water molecules will probably do little harm, although they may give rise to a certain dipole loss;* groups of molecules will involve conduction loss and a lowering of breakdown strength. In the case of paper and fabric boards and cylinders the cellulose must take up an appreciable quantity of the water, with the usual deleterious effects on its electrical behaviour.

The effects of water are generally more serious than those of polar groups, in that water immediately lowers the electrical breakdown strength, whereas dipole effects do not appear to do so, unless in the unusual event of the dielectric loss becoming so great as to cause thermal breakdown.

In considering future possibilities of dielectric materials, therefore, it seems desirable that stress be laid first of all on the elimination of condensation reactions rather than on the elimination of dipole effects. The production of a material having the desirable characteristics of bakelite by means of a reaction from which water is not obtained would be a great advance. The essence of these desirable characteristics is believed to be the " three-dimensional " structure of the phenol and urea resins. Whether this type of structure can be conveniently attained by other means than condensation is for the chemist to decide. Such reactions as the vulcanization of rubber, and the cross-linking of styrene by *p*-divinyl benzene, suggest that the realization of such an aim is not beyond hope.

Dr. L. Hartshorn, and **Messrs. N. J. L. Megson** and **E. Rushton** (*in reply*): We explained at the outset that our primary object was to stimulate a discussion on plastics and insulation from both the chemical and electrical standpoints, and we are highly gratified by the response which has been forthcoming from both sides. In the main there appear to be no fundamental divergences of opinion on the factors which limit the use of existing materials, and the general directions in which progress should be sought, but naturally there are considerable differences of opinion on points of detail.

We shall consider in the first place the comments and suggestions bearing on experimental investigation. Prof. Jackson advocates measurements on materials of simpler chemical composition; Mr. Martin and Mr. Pattman suggest the use of filled materials moulded under practical conditions, i.e. materials of a more complex character than our films; while Dr. Jordan suggests experiments on monomolecular films. We appreciate the merits of all these suggestions, and hope that they will in due course all be acted upon. Their diversity, however, does suggest that our choice of thin films of a pure resin of the greatest commercial importance is a good compromise between the severely practical and the purely theoretical, which forms a convenient starting-point for research along both lines. It is to be remembered that even in a commercial moulding the resin exists in the form of thin films which bind together the particles of filler. It is true that these films are produced under pressure, and Mr. Pattman's suggestion that the pressure might affect the physical properties should not be overlooked. We hope to look into this question, though we are inclined to think that the general measure of agreement between our results and the experience of users of commercial materials, such as Mr. Dunton, suggests that the effect of pressure on the resin itself is not a dominating factor. We certainly agree with Mr. Martin's point that our films, which are very thoroughly cured, will be in a very different state from those in many materials made under commercial conditions. Mr. Martin's curves (Fig. A) are eloquent on this point, and Mr. Brown's comparison of the conditions obtaining in laminated boards and cylinders also bears upon it. Commercial mouldings and pressings undoubtedly often contain water and phenolic compounds in proportions quite different from those which obtain in our carefully-prepared films, and their power factors are correspondingly higher, especially at higher temperatures. We regard our present results as indicating the best to be expected from resins of their type. The variations of properties obtained by various processes, considered in relation to their cost, might well be investigated. We hope to extend our own work to the study of boards and mouldings in due course.

Prof. Jackson points out that on the theoretical side our investigation is by no means complete, and we are in entire agreement with him on this matter. The effect of chemical factors such as impurities and substituents cannot be completely determined by measurements over the restricted range of frequencies discussed in this paper. We have indeed extended our working range so that it now covers the whole range of power, audio, radio, and television frequencies, but the evidence still remains incomplete. We are not even convinced that it will be possible to explain the observed changes of power factor for hardened resins in terms of a dipole moment and a single relaxation-time, but the important fact remains that the power factor under given working conditions can be modified by the chemical factors we have discussed, and for the moment we are not prepared to say more than that. This lack of evidence also accounts for the omission, on our part, of any attempt to discuss the nature of the underlying physical mechanism in hardened resins. We agree with Prof. Jackson as to the importance of a knowledge of the forces restricting the motion of polar groups in materials of all kinds, and especially solids, but the fact that investigators tackling this question have been driven to use such vague terms as "apparent internal viscosity" in order to describe their results, is itself a sufficient indication of the very tentative character of existing theoretical work on this problem. We did not feel justified in applying such considerations to our own experimental work, and contented ourselves with a mere reference to this side of the problem in the more general part of the paper. We welcome the emphasis which Prof. Jackson lays on this question and appreciate the elegance with which Mr. Moullin makes the same point in his graphic concluding metaphor. We strongly support Prof. Jackson's contention that more research work on mechanical properties is called for.

---

* Cf. J. Errera and H. Sack: *Transactions of the Faraday Society*, 1934, vol. 30, p. 687.

Discussion on the chemical aspects of the problem has centred to a large extent round the question of water-content, and there is a considerable measure of agreement that the water liberated by the condensation reaction which occurs during hardening, constitutes a serious disadvantage. Messrs. Brown, Bennitt, Messent, and Sillars, all stress this point, which incidentally answers Mr. Potter's objection to our use of alcohol as a solvent. The absolute alcohol used would probably contain less water than would be liberated by the reaction, and, as other speakers point out, our severe stoving conditions would remove this water with unusual completeness. The more general question is, however, clearly one of great practical importance. Mr. Sillars claims that the elimination of condensation reactions is more important than the elimination of dipole effects, and from an economic standpoint this may be true, though the two things are in practice so closely connected that discrimination is difficult. In any event, we agree with those speakers who urge that the production of a three-dimensional structure without condensation reactions demands the chemist's immediate consideration.

The question of water absorption, which is not necessarily the same as that of water content, is discussed by Mr. Potter, who doubts whether the polar OH groups are responsible for the water absorption of the phenolic resins. We agree that non-polar materials like paraffin wax and benzene do absorb some water, but the amount is very small compared with that absorbed by most polar materials. The polar character of the water molecule itself might well account for this small absorption. The water absorption of urea-formaldehyde is quite in accordance with our suggested explanation, since although free from OH groups it does contain polar CO groups. We do not follow Mr. Potter's contention that a dielectric constant which varies with humidity but not with thickness can be explained on the assumption of a surface film. Our argument may be elaborated as follows. The thickness of the surface film t_2 would clearly be independent of the thickness of the resin film t_1. If κ_1 and κ_2 are the dielectric constants of the resin and water-film respectively, the value κ for the combination will be:—

$$\kappa = \frac{\kappa_1\left(1 + \frac{t_2}{t_1}\right)}{1 + \frac{\kappa_1 t_2}{\kappa_2 t_1}}$$

Now since κ_2 is not equal to κ_1, the measured value of κ can only be independent of the film thickness t_1 if $t_2 = 0$, i.e. if there is no surface film.

The values of water absorption on which we comment are those usually obtained for thick specimens. Examples are those given by Leopold and Johnston, whose paper is quoted in our Appendix. Such values may of course be useful for comparative purposes in industrial testing.

Our Table 2 of representative values has called forth some criticism, but on the whole less than might have been expected, having regard to the unrepresentative character of most of the data obtained for insulating materials. We tried, in compiling this Table, to give a rough guide to performance under ordinary working conditions, and therefore deliberately excluded details of test methods, for values which depend critically on such factors are clearly of correspondingly little value for our purpose, and a host of footnotes giving conditions of test would merely tend to obscure the little information such values can supply. For the same reason we excluded values of the "intrinsic electric strength" to which Dr. Austen refers. At the present time there appears to be no evidence that such values have any bearing on the behaviour of the material in ordinary practice. We agree that the matter is of great theoretical interest, and that one of the objects of future research should be the correlation of values of "intrinsic electric strength" and structure, but so few measurements of this kind have been made on plastics that we believe that any attempt to discuss the results would be premature.

We welcome the additional data presented by Messrs. Dunton, Jackson, Brown, Messent, and Moullin. Our value for chlorinated diphenyl was taken from the paper Mr. Moullin has quoted. The omissions he has noted were merely due to considerations of space. In reply to Mr. Dunton, we have no information regarding the use of this material for mouldings, though we understand that chlorinated diphenyl plastics can be cast in the same way as the natural waxes.

Replying to Mr. Bennitt's query about the evidence for the structure of the resins, we did not mean to imply that the experiments with varying proportions of formaldehyde alone suggested that particular structure, but that, since additional phenol, formaldehyde, and hexamine had no marked effect, it was reasonable to suppose that the properties observed were characteristic of a resin of definite structure. One might, of course, assume that the resins were all different and that the agreement in properties was mere coincidence, but that is very improbable.

The actual structure suggested is based on chemical evidence and is fairly generally accepted.

We are not quite sure whether Mr. Potter's objection to our molecular model is based on chemical or physical considerations. Probably no molecular model could claim to give a correct picture of a physical structure, but our model is, at any rate, more nearly correct than the usual graphic formula, for it does show a real three-dimensional structure. The assumptions made in its construction are that the sizes of the atoms in the resin are the same as those found for organic compounds which have been analysed by X-ray methods, that the benzene ring retains its usual size and shape, and that the tetrahedral angle between the four bonds of the aliphatic carbon atom is preserved in the structure. We merely claim that a model which embodies so much physical and chemical evidence is not likely to be seriously misleading and is very helpful in visualizing the type of structure in question.

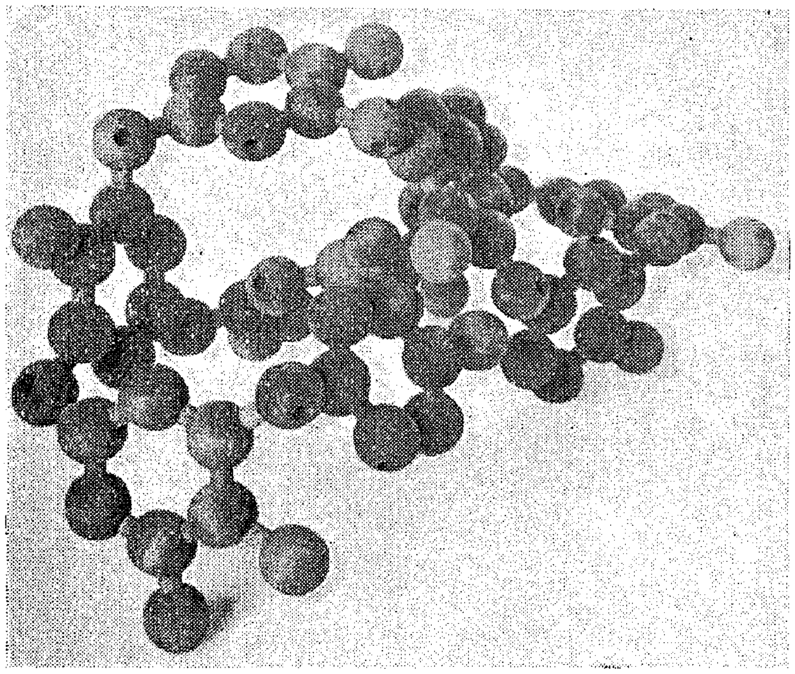
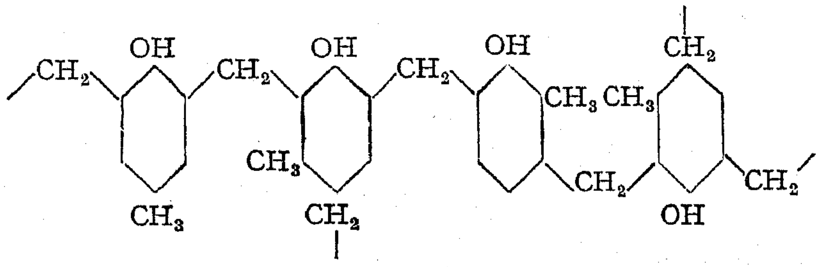


Fig. C.—Molecular model of heat-hardened phenolic resin.

It may be of interest to explain that models of the various plastics such as were shown during the reading of the paper can be made simply and cheaply in the following manner. Wooden ball-feet, consisting of spherical balls with wooden pegs attached (see Fig. C) are drilled in suitable jigs, so that holes are made either at 120° or 109° to the peg. Those with holes at 120° in the same plane with the peg can be readily assembled into hexagonal rings, simulating benzene, while those with holes at 109° (the tetrahedral angle) give, when joined together, aliphatic chains of the paraffin type. Substituents can be plugged into vacant holes.

Mr. Martin's objection to the term "plastics" is a natural one, but it has now become so widely used for a particular group of materials that a change at this stage would probably only add to such confusion as may exist.

Several questions remain to be answered. In reply to Mr. Langwell, we have not done any work on the possibility of accelerating the polymerization of polystyrene, but it is an attractive idea. To Mr. Gardner, we do not consider it likely that it will be possible in the near future to forecast the effect on electrical properties of a change in the cresol fraction used. Theoretically, the comparatively sluggish bifunctional *o*- and *p*-cresols cannot form heat-hardening resins, while the trifunctional *m*-cresol can do so readily. When mixtures of the three are used, the bifunctional cresols may form part of a three-dimensional structure of the type



Structures of this type would have to be studied quantitatively before predictions could be attempted.

We cannot offer Mr. Potter any explanation of the undulations in the curves for dielectric constant in Fig. 5. They are clearly connected with the absorbed water, since the curves for the dried resin do not show them. The dielectric constant of water itself diminishes with rise of temperature; on the other hand, its conductivity increases, and this often causes an increase in the effective dielectric constant of substances containing water. Variations in the relative magnitudes of two such effects might account for the undulations.

It is equally difficult to give Mr. Messent a detailed explanation of the decrease in power factor of the dried resin with rise of temperature. We have ascribed the power factor to the motion of the polar OH groups against the action of a controlling force of a frictional or viscous type. The diminution of power factor is therefore probably accounted for by changes in this controlling force with rise of temperature. Such changes are quite probable, for it is well known that viscosity, for example, diminishes rapidly with temperature. We are not entitled to assume, however, that the forces concerned in this material are those of ordinary viscosity, and can only say that we believe the explanation is to be sought on these lines.

Mr. Gardner's question, as to whether lower power-factors are to be expected from thermoplastic resins only, is one of great difficulty. The cross-linking required to yield a three-dimensional heat-hardened product does seem to necessitate the existence of active substituent-directing groups, which, being polar, tend to produce a high power factor. We are not prepared to say, however, that the production of a heat-hardening hydrocarbon is a theoretical impossibility. Polystyrene can be cross-linked with divinyl benzene, and there seems to be no reason why further developments in this direction should not be possible.* As such a development would also meet the demand of several other speakers for the elimination of condensation reactions, it may be regarded as the ultimate goal towards which the discussion as a whole is pointing.

---

* Cf. a recent paper by R. G. W. Norrish and E. F. Brookman: *Proceedings of the Royal Society*, A, 1937, vol. 163, p. 205.

CURRENT RATING AND IMPEDANCE OF CABLES IN BUILDINGS AND SHIPS

By H. C. BOOTH, E. E. HUTCHINGS, B.Sc.(Eng.), Associate Member, and
S. WHITEHEAD, M.A., Ph.D., Associate Member.

[REPORT (REF. F/T115) OF THE BRITISH ELECTRICAL AND ALLIED INDUSTRIES RESEARCH ASSOCIATION.]

(*Paper first received* 30*th April, and in final form* 23*rd July,* 1937; *read before the* TRANSMISSION SECTION 19*th January,* 1938.)

SUMMARY

An account is given of the investigations on which were based much of the revision and, in particular, the new rating and voltage-drop tables, with Appendix 5, of the Tenth Edition of the I.E.E. Regulations for the Electrical Equipment of Buildings. The results of these investigations will, subject to the approval of the I.E.E. Council, be embodied in the next edition of the Regulations for the Electrical Equipment of Ships. This work, carried out partly at the National Physical Laboratory and partly at the E.R.A. auxiliary laboratory, dealt mainly with the effect of alternating current instead of direct current; of new modes of installation such as heavy cables in cleats, large groups of cables in conduits, ducts, chases, and surface wiring systems; the use of bare copper rods, long vertical runs in chases or shafts, etc.; and with the effect of steel bulkheads or steel-reinforced concrete structures in proximity to a.c. systems. While the earlier figures of the Ninth Edition were largely confirmed as general averages for certain conditions, a large number of new circumstances were investigated in detail, and the values observed were theoretically substantiated to the accuracy permitted by the conditions. The main purpose of the paper is to indicate the more accurate figures on which the necessarily condensed average tables of the Regulations are based, but the detailed results have also other applications.

The experimental work is classified broadly in three sections, as follows:—

(*a*) The current-carrying capacities of large cables run in air in various configurations.
(*b*) Effects due to proximity of large cables to steel structures. In this section of the research, cables were run parallel to a steel plate, through holes in a steel plate, and through a steel-rod structure (to simulate reinforced concrete). Tests were made on both single-phase and 3-phase systems.
(*c*) The properties of small rubber-insulated cables (sizes up to 0·5 sq. in. were included in some conditions of test) installed in a variety of methods such as in conduits, ducts, etc.

The results of the investigations show that the reduction in current-carrying capacity due to skin effect and sheath losses is only serious in cables of 0·5 sq. in. conductor section and above. The increase in current rating due to better cooling conditions when cables are spaced farther apart may be partially or wholly counterbalanced in lead-covered cables by increase in sheath losses. In the case of bare copper rods run vertically, the temperature of which may be higher than that of insulated cables, it was found that excessive heating of rubber-insulated cables connected to the rods occurred near the joints.

When cables carrying alternating current are run close to a steel plate the impedance is increased, and in some cases the effect on the voltage-drop may be sufficient to necessitate reducing the current rating of the cable below that based on the permissible temperature-rise. Also, in the case of a reinforced-concrete building, steelwork may be so heated owing to heavy currents in large cables as to cause serious expansion.

INTRODUCTION

In the Tenth Edition of the Regulations for the Electrical Equipment of Buildings, the ratings, except for small cables, are based on a maximum temperature-rise of 20 deg. F. (11·1 deg. C.) for rubber-insulated cables and 50 deg. F. (27·7 deg. C.) for paper-insulated cables; and, where actual ratings are given in the paper, they refer to these values. For any other temperature-rise which may later be adopted the corresponding ratings can easily be calculated as shown. The more general conclusions in each section will be unaffected by a change of this nature.

(1) CURRENT-CARRYING CAPACITY (D.C. AND A.C.) OF PAPER-INSULATED AND RUBBER-INSULATED CABLES UNDER VARIOUS CONDITIONS OF INSTALLATION

(a) Scope of Investigation

The investigation was undertaken to determine the current ratings of two and three single-core cables run under various conditions. Ratings were required for both rubber- and paper-insulated cables, (i) with direct current, and (ii) with alternating current at 50 cycles per second.

New rubber-insulated and impregnated-paper-insulated lead-covered cables made by members of the Cable Makers' Association, for a working voltage of 660 volts, were used. The nominal cross-sectional areas of both types of cable were 0·1, 0·25, 0·5, and 1·0 sq. in. The dimensions and resistances of all the cables complied with the requirements of B.S.S. No. 7—1926.* The length of each cable was about 20 ft.

The current-carrying capacity of each cable was determined by the measurement of temperature-rise for a range of appropriate currents, both direct and alternating. From the results of these measurements the current required to produce the permissible temperature-rise under the given conditions of installation was determined by interpolation.

---

* The changes subsequently introduced in B.S.S. No. 480 as compared with B.S.S. No. 7 are not material to the present investigation.

Seven conditions of installation, which were considered to be representative of the more usual conditions of practice, were investigated. Details of these are given in Table 1.

Table 1

Conditions of Laying of Cables

1	2	3	4	5	6	7
Condition of laying	Size of cable	Paper-insulated lead-covered cables		Taped and braided rubber-insulated cables		Type of rack, method of laying, etc.
		Distance between cable centres	Distance between cable centres and wall or floor	Distance between cable centres	Distance between cable centres and wall or floor	
	sq. in.	in.	in.	in.	in.	
A	1·0	1·8*	0·9†	1·75*	0·9†	No racks; cables lying on floor in contact with each other and with floor
	0·5	1·3*	0·65†	1·3*	0·65†	
	0·25	1·0*	0·5†	0·9*	0·45†	
	0·1	0·7*	0·35†	0·6*	0·3†	
B	1·0	3·6	0·9†	3·5	0·9†	No racks; cables in contact with floor and separated from each other
	0·5	2·6	0·65†	2·6	0·65†	
	0·25	2·0	0·5†	1·8	0·45†	
	0·1	1·5	0·35†	1·2	0·3†	
C	1·0	3·6	2¼	3·5	2¼	Raised from floor and separated
	0·5	2·6	2¼	2·6	2¼	
	0·25	2·0	1¼	1·8	1¼	
	0·1	1·5	1¼	1·2	1¼	
D	1·0	1·8*	0·9†	1·75*	0·9†	Clamped against wall; cables in contact with each other and with wall
	0·5	1·3*	0·65†	1·3*	0·65†	
	0·25	1·0*	0·5†	0·9*	0·45†	
	0·1	0·7*	0·35†	0·6*	0·3†	
E	1·0	3·5	2¼	3·5	2¼	Porcelain in iron frame on wall
	0·5	3·5	2¼	3·5	2¼	
	0·25	2·0	1¼	1·8	1¼	Wooden cleats on wall
	0·1	1·5	1¼	1·2	1¼	
F	1·0	3·5	2¼	3·5	2¼	Porcelain in iron frame on wall; 3-phase
	0·5	3·5	2¼	3·5	2¼	
	0·1	3·5	2¼	—	—	
G	0·25	2·0	1¼	1·8	1¼	Wooden cleats on wall; 3-phase
	0·1	1·5	1¼	1·2	1¼	

* Cables touching. † Cables touching wall or floor.

In the tests on paper-insulated, lead-covered cables the sheaths were bonded at each end. The bonding was effected by means of several strands of tinned copper wire soldered to the sheaths. The resistance of the bond was not greater than that of an equal length of lead sheath.

(b) Procedure

In the determination of the temperature of the conductor, both the method of inserted thermocouples and that depending on the change of the conductor resistance were used. In the former, five couples made up of copper-constantan of 0·0092 in. diameter were inserted at equidistant points in the central 10-ft. length of each cable. In the other method the change of resistance was directly determined by means of a double bridge. The results obtained by the two methods were in good agreement. In general, the resistance method was adopted as being more convenient; it has also the advantage that it is not necessary to drill into the cable at a number of points, with the consequent possibility of leakage of oil.

The smallness of the temperature-rise permitted for rubber-insulated cables, which was only 11·1 deg. C., made the obtaining of a consistent series of ratings a matter of considerable difficulty. A very high degree of accuracy is especially called for in the temperature to which the basic or "cold" resistance values refer. The temperature of the air was obtained from a series of thermometers reading to a hundredth of a degree C. hung near the cable, but at a sufficient distance not to be appreciably affected by radiation or convection from it.

In determining the rating of cables which are superposed one above the other, and when one of the conductors on account of its position is necessarily hotter than the other, the rating has been based on the behaviour of the hotter cable. In the case of three cables laid up together and carrying 3-phase current there are additional differences beyond those due to position, consequent on the unequal sheath losses in the three cables. In the case of three lead-covered cables run in flat formation the losses in the two outers are unequal. In which of the two outers the greater sheath loss occurs depends upon the phase sequence. In determining the rating the most unfavourable condition was always taken, and the phase sequence was arranged so that the greater sheath loss occurred in the uppermost cable, i.e. in the cable which was most affected by mutual heating.

(c) Thermal Resistivity of Dielectric

The thermal resistivity of the dielectric of all the cables tested was determined, in order to ensure that they could be regarded as typical samples, and also in order that an approximate correction could, if required, be estimated for the ratings of cables having coverings of very different thermal resistivity. In the lead-covered cables the determination was effected by measuring the changes in the resistances of the conductor and sheath, and thence deducing their temperatures. For this purpose the temperature coefficient of a sample of lead taken from the sheath of each cable was specially determined.

The values of thermal resistivity of the dielectric for the various sizes of paper-insulated cables ranged from K* $= 630$ to $K = 800$, the mean value being $K = 730$.

In the case of the rubber-insulated cables the thermal resistivity was obtained as a mean for the whole covering, which includes the taping and braiding in addition to the rubber. The temperature of the outer surface of the covering was assumed to be the same as that of a fine copper wire which was bound round it over a length of some 3 yards, and over which a single layer of rubber tape was then wrapped. This wrapping of rubber tape was continued at both ends for some distance beyond the region occupied by the copper winding so that the heat transference from the core should be properly radial over the part tested. The temperature of this copper winding was derived from measurements of its resistance, the temperature coefficient of which had been specially determined.

In order to afford a check on the method, thermocouples were wrapped under the rubber tape, at several points on the surface of the cable. The temperature indication of these was in every case some 0·2 or 0·3 degree Centigrade lower than that derived from the change of resistance of the wire wrapping.

In these circumstances the method giving the higher indication of surface temperature was considered likely to be the more correct, and in the calculation of thermal resistivity the temperature derived from the resistance of the wire was preferred to that indicated by thermocouples. A probable explanation of the discrepancy lies in the non-uniformity of the surface temperature of the rubber-insulated cable; the closely wound spiral of wire will naturally give a better indication of mean temperature than will a few isolated thermocouples.

The values of thermal resistivity of the dielectric of the rubber-insulated cables determined by the wire method ranged from $K = 630$ to $K = 720$, the mean value being $K = 670$.

(d) Relation between Current and Temperature-Rise

The results obtained for the temperature-rises corresponding to various current loadings were examined to determine the best average value to be adopted for the index "n," if it is assumed that the two quantities are connected by the relation—

$$\theta = cI^n$$

where θ is the temperature-rise of the conductor above the surrounding air and I is the current in amperes, c being a constant depending on the conditions of installation.

In general, the currents at which tests were carried out were adjusted to produce a temperature-rise as close as possible to 11·1 deg. C. in rubber-insulated cables, and to 27·7 deg. C. in paper-insulated cables. The index n was calculated for each cable by taking two pairs of values of current and temperature-rise and substituting them in the formula—

$$n = \frac{\log(\theta_1/\theta_2)}{\log(I_1/I_2)}$$

The examination of a large number of results shows that the mean value for n lies between 1·6 and 1·8.

A later series of tests, in which rubber-insulated cables were loaded to give a wider range of temperature-rise (from 2·5 to 32 deg. C.), gave an exponent of 1·84. Approximately the same value was obtained in tests, described in (*f*) below, on 3- and 4-core paper-insulated cables for a temperature-rise varying between 20 and 60 deg. C., and it therefore appears that this value may be used in extrapolating over quite wide temperature limits for cables of 0·1 sq. in. to 1·0 sq. in. copper section. In obtaining the values of current loading corresponding to the standard temperature-rise, extrapolation was not usually resorted to. The method generally adopted was so to adjust the current that values were obtained for the temperature-rise closely approximating to the standard value. The logarithms of current and temperature-rise were then plotted for the experimental values, the best straight line drawn through them, and the required value for the current producing the standard temperature-rise obtained by interpolation.

The current rating I corresponding to any temperature-rise θ different from the value θ_0 permitted in the Tenth Edition of the Wiring Regulations may, however, be calculated by multiplying the values given therein by $(\theta/\theta_0)^{0\cdot54}$. It can be shown that the error in current rating thus introduced will not exceed 5 per cent so long as the ratio θ/θ_0 is not less than 0·56 or greater than 1·8.

---

* K is expressed as the temperature-difference, in degrees Centigrade, per watt transmitted between the opposite faces of a centimetre cube.

Table 2

Rating Factors for Cables under Various Conditions of Laying*

1	2	3		4	5	6		7	8
Conditions of laying (see Table 1)	Nominal size of conductor, sq. in.	Paper-insulated, lead-covered cables				Rubber-insulated cables taped and braided			
		Ratio of a.c. to d.c. rating under same conditions		Ratio of rating under given conditions to rating under Condition E		Ratio of a.c. to d.c. rating under same conditions		Ratio of rating under given conditions to rating under Condition E	
		Measurement	Calculation	D.C.	A.C.	Measurement	Calculation	D.C.	A.C.
A	1·0	0·85	$0\cdot85_4$	0·93	0·98	0·90	$0\cdot90_7$	0·92	0·93
	0·5	0·98	$0\cdot95_4$	0·88	0·95	0·98	$0\cdot97_4$	0·87	0·86
	0·25	0·99	$0\cdot98_6$	0·86	0·87	1·00	$0\cdot99_3$	0·87	0·87
	0·1	0·99	$0\cdot99_7$	0·87	0·87	1·00	$0\cdot99_9$	0·85	0·85
B	1·0	0·81	$0\cdot79_0$	0·98	0·99	0·96	$0\cdot94_3$	0·99	1·07
	0·5	0·95	$0\cdot92_6$	0·96	1·00	0·97	$0\cdot98_6$	0·94	0·92
	0·25	0·97	$0\cdot97_3$	0·97	0·95	1·00	$0\cdot99_6$	0·93	0·93
	0·1	0·99	$0\cdot99_3$	1·05	1·06	1·00	$0\cdot99_9$	0·93	0·93
C	1·0	0·80	$0\cdot79_0$	1·03	1·02	0·93	$0\cdot94_3$	1·05	1·11
	0·5	0·91	$0\cdot92_6$	1·02	1·02	0·97	$0\cdot98_6$	1·02	1·00
	0·25	0·97	$0\cdot97_3$	1·04	1·03	1·00	$0\cdot99_6$	1·04	1·04
	0·1	0·99	$0\cdot99_3$	1·12	1·12	1·00	$0\cdot99_9$	1·00	1·00
D	1·0	0·87	$0\cdot85_4$	0·84	0·90	0·93	$0\cdot90_7$	0·87	0·90
	0·5	0·95	$0\cdot95_4$	0·83	0·87	0·96	$0\cdot97_4$	0·83	0·80
	0·25	0·98	$0\cdot98_6$	0·82	0·81	1·00	$0\cdot99_3$	0·81	0·81
	0·1	0·98	$0\cdot99_7$	0·84	0·83	1·00	$0\cdot99_9$	0·83	0·83
E	1·0	0·80	$0\cdot79_5$	1·00	1·00	0·89	$0\cdot94_3$	1·00	1·00
	0·5	0·91	$0\cdot90_4$	1·00	1·00	0·99	$0\cdot98_8$	1·00	1·00
	0·25	0·99	$0\cdot97_3$	1·00	1·00	1·00	$0\cdot99_6$	1·00	1·00
	0·1	0·99	$0\cdot99_3$	1·00	1·00	1·00	$0\cdot99_9$	1·00	1·00
F	1·0	—	—	—	0·87	—	—	—	0·96
	0·5	—	—	—	0·94	—	—	—	0·97
	0·1	—	—	—	1·01	—	—	—	—
G	0·25	—	—	—	0·97	—	—	—	0·98
	0·1	—	—	—	0·98	—	—	—	0·99

* All lead-covered cables were bonded at each end. The rating factors for Conditions F and G apply to balanced 3-phase loading, the phase sequence being arranged to give the maximum heating effect.

In Appendix II theoretical formulae for calculating the current ratings are given, depending on a knowledge of certain thermal-dissipation coefficients. General values of these coefficients have since been determined, and calculation on the basis of these values gives satisfactory agreement with the present tests. However, the conditions envisaged in the present section are well defined, and it was considered more direct to use the carrying capacities actually determined rather than values calculated from dissipation coefficients which have themselves been determined from similar tests. The measured values are, in fact, in accord with the general theoretical scheme, on the assumption that the emissivity of braided coverings is unity and that of plain lead sheaths is low, corresponding to a quasi-bright surface.

(e) Current-Carrying Capacities of Single-Core Cables

The results obtained are summarized in Table 2 in the form of ratios, and actual ratings have been plotted in Figs. 1 to 6. From these curves the ratings of other sizes of similar cables may be derived by interpolation. Columns 3 and 6 give the ratio of a.c. rating to d.c. rating under the same conditions of installation, which is compared with the theoretical ratio. The latter can in this case be accurately calculated by the method given in Appendix II. From these figures it is evident that the reduction in current-carrying capacity due to skin effect and sheath losses is only serious in cables having a cross-sectional area of $0 \cdot 5$ sq. in. or greater.

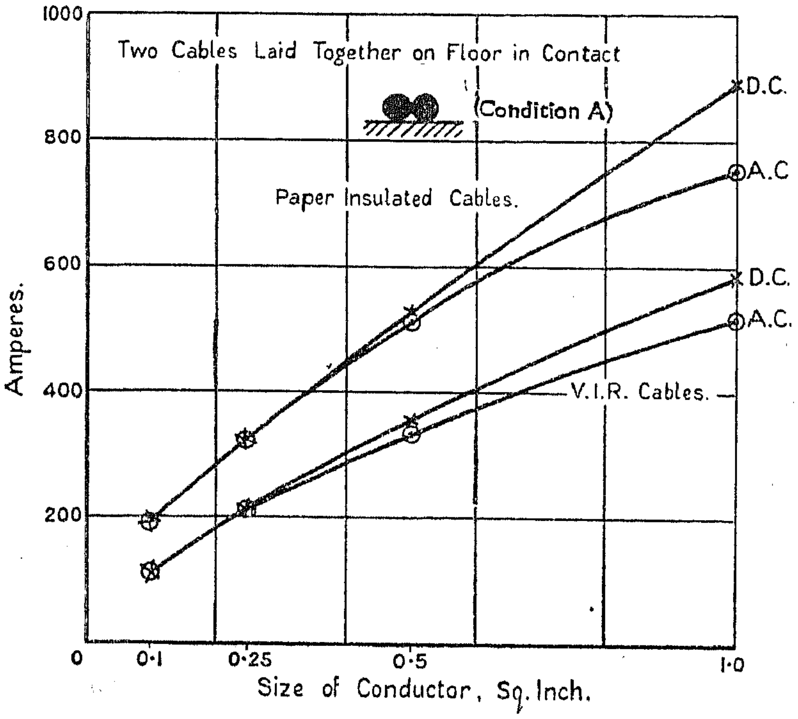


Fig. 1.—Two cables laid together on floor in contact.

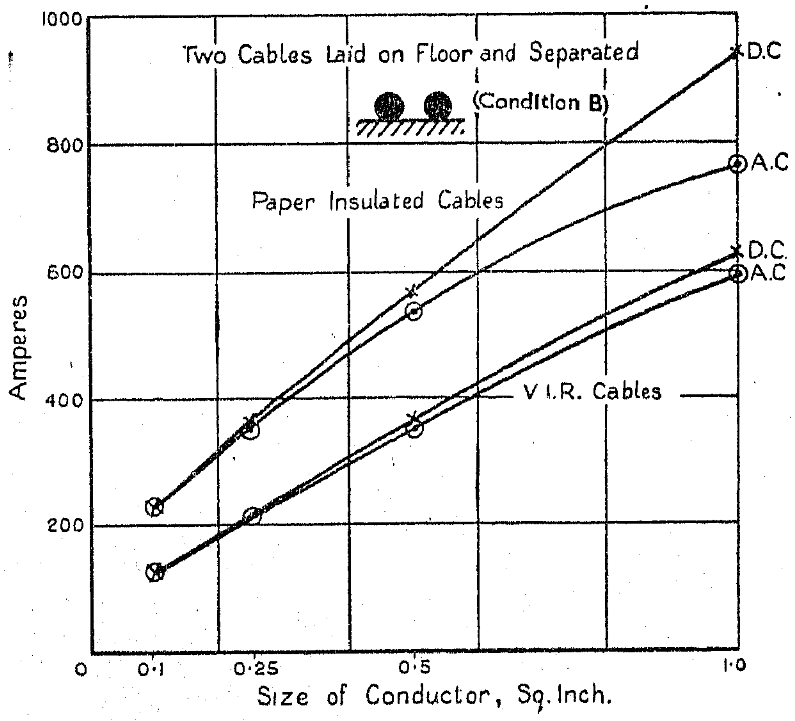


Fig. 2.—Two cables laid on floor and separated.

The effect of increasing the spacing of cables is generally to improve the cooling conditions, but the increase in current-carrying capacity which may be expected on this account may be wholly or partially counterbalanced in lead-covered cables, when carrying alternating currents, by the corresponding increase in sheath loss.

The rating factors given in Table 2, cols. 4, 5, 7, and 8, show more clearly the effect of installation upon the current-carrying capacity. In calculating these rating factors, the current-carrying capacity for each size of cable installed under any given condition has been referred to the corresponding value for two such cables run horizontally one above the other on a vertical wall, supported by cleats and separated from one another and from the wall by specified distances. This method of installation has been termed "installation under defined conditions" in the Tenth Edition of the I.E.E. Wiring Regulations.

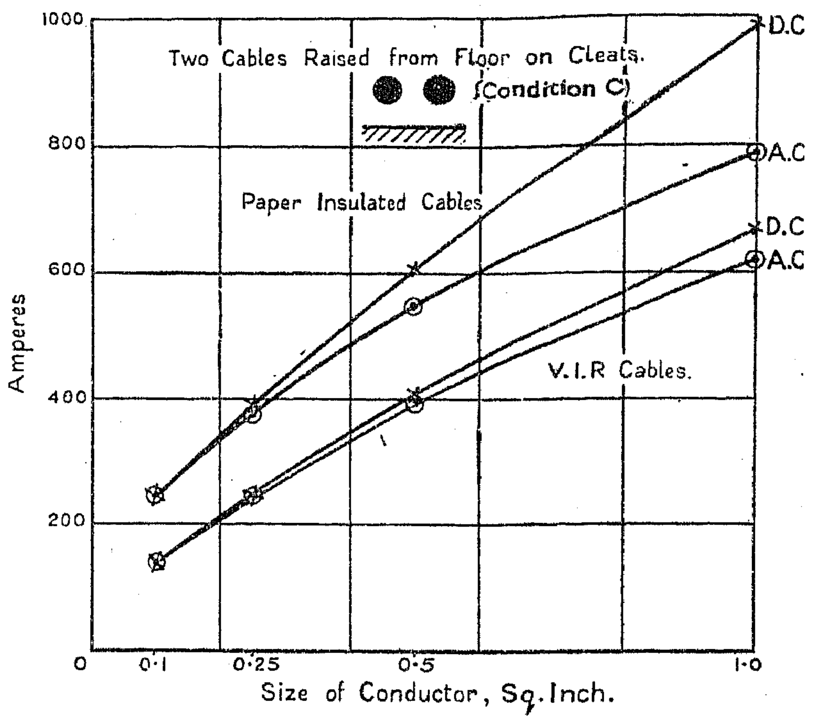


Fig. 3.—Two cables raised from floor on cleats.

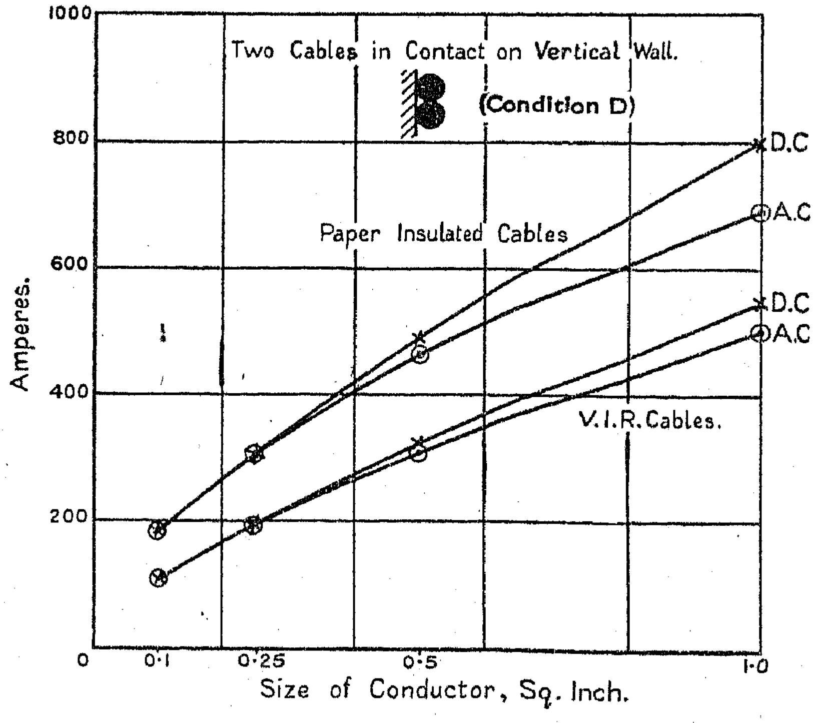


Fig. 4.—Two cables in contact on vertical wall.

The results in all cases apply to cables run horizontally. In the tests on cables run vertically it was found that the upper part was generally hotter than the mean temperature of the whole cable. Accordingly, the question of vertical cable-runs will be treated separately in Section (3).

(f) Three-Core and Four-Core Cables

A series of tests was made to determine the current-carrying capacity of 3- and 4-core 600-volt plain lead-sheathed, paper-insulated cables with circular conductors. Two sizes were investigated, viz. 0·25 sq. in. (both 3- and 4-core) and 0·4 sq. in. (4-core). Balanced 3-phase loading was adopted as giving the worst condition, the fourth core (of the same size as the other three) in the case of 4-core cables being idle. The cables were in 30-ft. lengths and were installed horizontally in mild-steel cable hangers along the wall and a few inches below the covers of a special draught-free test pit.

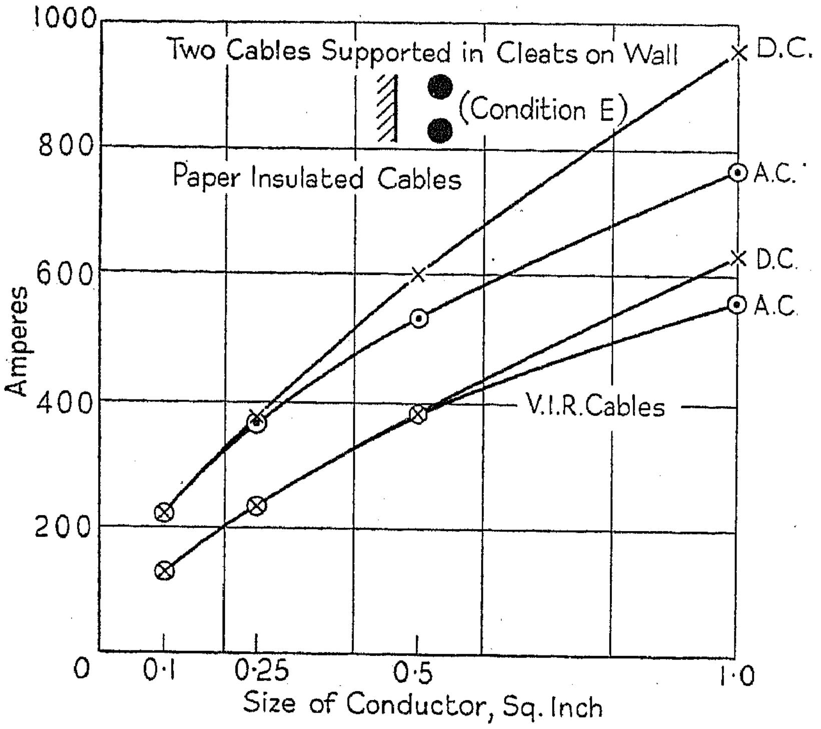


Fig. 5.—Two cables supported in cleats on wall.

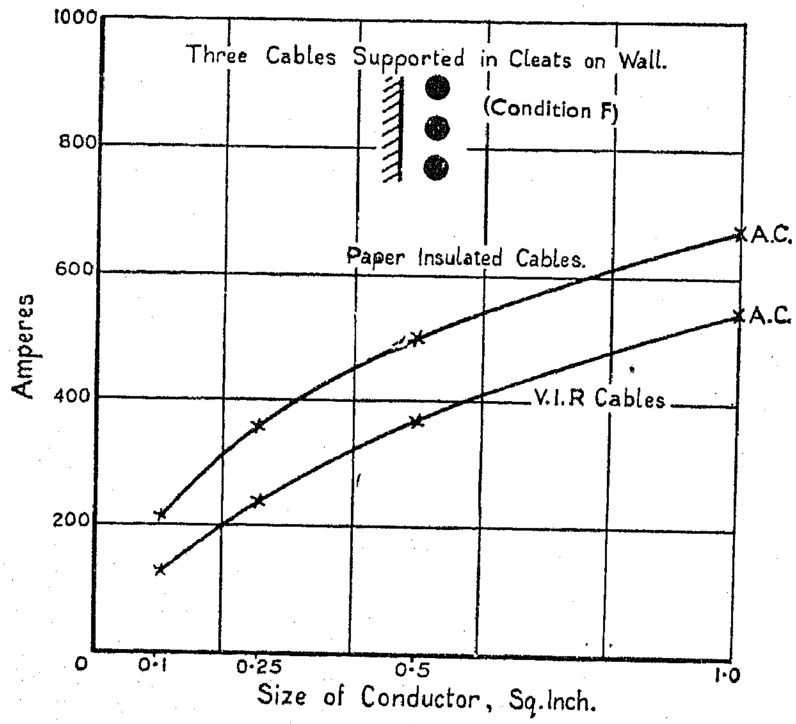


Fig. 6.—Three cables supported in cleats on wall.

The tests covered a range of temperature-rise between 20 and 60 deg. C., and the temperature-rise was found to be proportional to the current raised to the power 1·9.

The current rating of the 4-core cable was found to be only 3 per cent higher than that of the corresponding 3-core cable, and the values obtained agreed closely with those calculated on the assumption that such cables are thermally equivalent to six single-core cables of the same size bunched together [see Section (3) (*f*) (ii)].

(2) EFFECT OF STEELWORK ON LARGE LEAD-COVERED CABLES

(a) Cables Run Parallel to Steel Plate

(i) General.

This condition may occur in ships and also in large concrete buildings. In the first case, cables may be run in racks, etc., along a bulkhead or the side of the ship; in the second, cables may be run along a column or panel in which is embedded a steel plate, usually supported by one or two girders or channels; a 2-in. cover of concrete over the plate is the normal minimum.

It was decided to employ for test purposes a sheet of steel 18 ft. × 3 ft. × 0·4 in. thick, the steel being of normal type for the uses envisaged.*

The plate was laid on a concrete floor, and the cables were supported in a horizontal plane above the plate on wooden blocks. This arrangement did not give the worst thermal conditions, but, since the temperature-rise of the steel did not exceed 2·5 deg. C. in the centre for a 30 deg. C. rise in the cable cores, the heating of the steel may be neglected. The ambient air temperature above the steel was raised slightly—by not more than 2 deg. C. The temperatures of the cable cores were measured by increase of the d.c. resistance, while the temperatures of the sheaths and steel plate were determined by thermocouples, and the air temperatures by thermometers. The a.c. impedance was measured by means of a Campbell–Larsen potentiometer in conjunction with mumetal current-transformers and shunts. Since both single-phase and 3-phase tests were made, a.c. impedances are always given for one phase only, i.e. the impedance of one phase with a hypothetical neutral return at a great distance, carrying no current. In 3-phase tests an actual neutral wire is necessary, the location and balance of which has been described elsewhere.†

(ii) Effect of steel plate on current-carrying capacity.

The temperature-rise of a cable core in these conditions is proportional to a power of the heating current which is approximately the convection value of 1·6, but usually rather greater. The index is not influenced to any great extent by the proximity to steel, the cable spacing, or the bonding of the sheaths.

The additional losses due to the steel when the sheaths are insulated are mainly located in the steel itself and therefore do not cause so important a reduction in carrying capacity as in the case of larger cables with the sheaths bonded. Figs. 7 and 8 show the effect of proximity to steel for paper-insulated cables with plain lead sheaths bonded, the thermal dissipating effect of the steel itself, which actually increases slightly the rating of small cables where the additional losses are very small, being taken into account. For 3-phase tests the rating has been based on the temperature-rise of the hottest cable, which for small cables is the middle cable and for large cables is the outer having the greater sheath loss. Thus in a transposed system of large cables the reduction may be somewhat less than that given. The reduction of carrying capacity increases with spacing and size of cable and increases more and more rapidly as the steel is approached. In this effect the decrease of rating follows the increase of sheath losses, by which it appears largely, though not wholly, to be determined. The maximum possible reduction appears to be about 15 per cent.

---

* Typical figures for composition are: carbon, 0·16 per cent; manganese, 0·5 per cent; sulphur and phosphorus, less than 0·06 per cent. The electrical and thermal resistivities will be of the order of 12 microhm . cm. and 2·15 thermal ohm . cm. respectively.

† See Bibliography, (3).

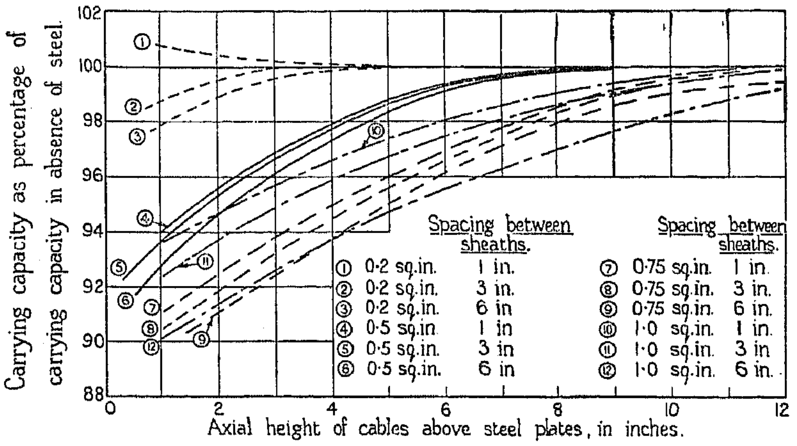


Fig. 7.—Effect of steel plates on carrying capacity of unarmoured single-conductor cables (sheaths bonded) —single-phase systems.

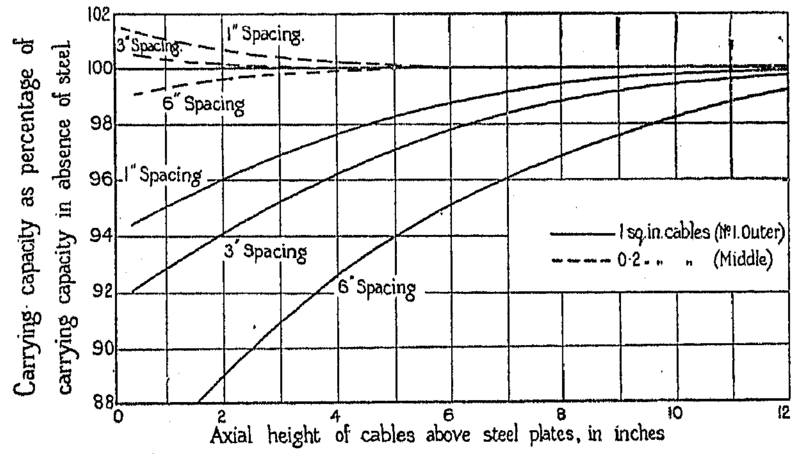


Fig. 8.—Effect of steel plates on carrying capacity of unarmoured single-conductor cables (sheaths bonded) —3-phase systems.

(iii) Effect of steel plate on line constants.

The overall impedance determines the length of cable for a given voltage-drop. The effect of the steel on this quantity is shown in some detail for single-phase systems in Figs. 9, 10, 11, and 12. In general, the order of the percentage increase in impedance is independent of the cable size over the range considered, being about 25 per cent at 1 in. distance from the steel for 6 in. spacing between sheaths, 20 per cent for 3 in. spacing, and 15 per cent for 1 in. spacing. Such approximations, though useful, are empirical, since the relative importance of reactance and resistance, which are affected by steel in a different manner, changes with size of cable.

When the sheaths are insulated an additional impedance arises from the magnetic flux, the hysteresis losses

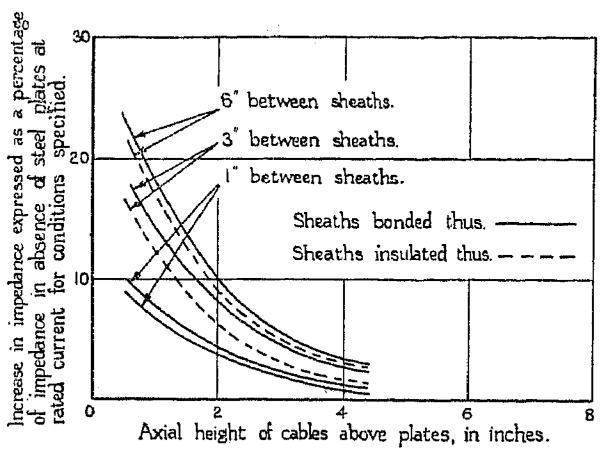


Fig. 9.—Effect of steel plates on impedance of 0·2-sq.in. unarmoured, single-conductor cables (single-phase).

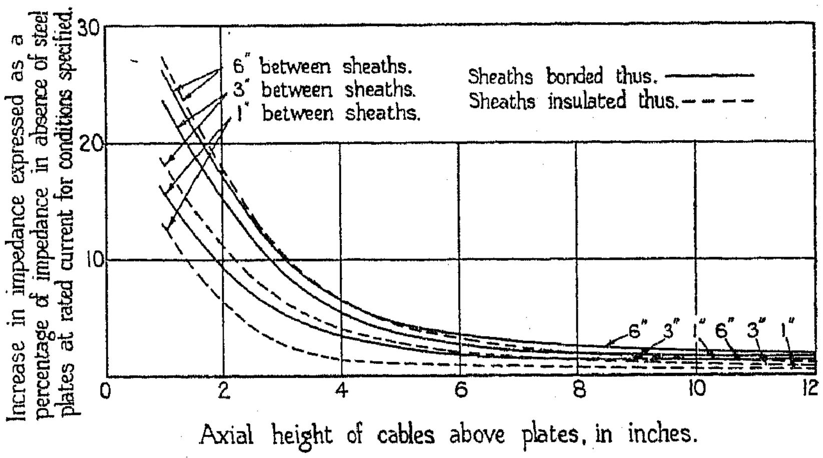


Fig. 10.—Effect of steel plates on impedance of 0·5-sq. in. unarmoured, single-conductor cables (single-phase).

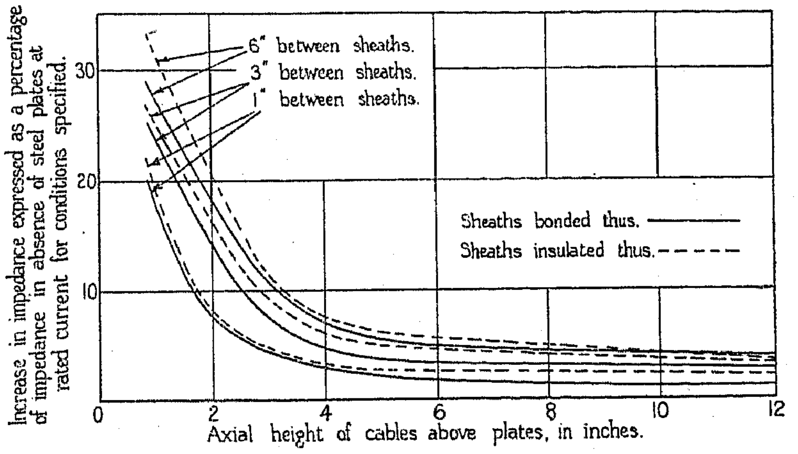


Fig. 11.—Effect of steel plates on impedance of 0·75-sq. in. unarmoured, single-conductor cables (single-phase).

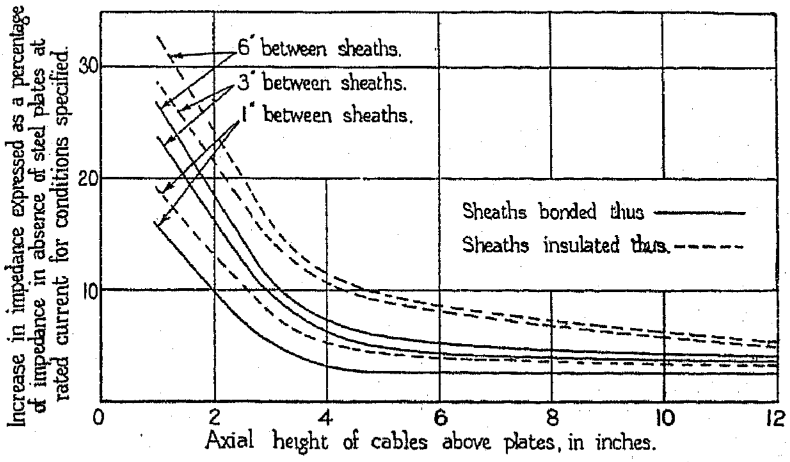


Fig. 12.—Effect of steel plates on impedance of 1·0-sq. in. unarmoured, single-conductor cables (single-phase)

and eddy currents in the steel, and proximity effects in the cores of the cables. The last effect should be small and is the only one which depends on the size of the cable *per se*. Accordingly, the absolute increase of resistance and reactance in microhms per cm. should be roughly independent of the size of the cable. This is the case, except when the cable is very close to the steel, and values observed at currents not widely different (to avoid change in saturation) are given in Fig. 13. When very close to the steel the larger cables have higher resistance-increments and rather lower inductance-increments.

In a previous paper* it has been shown that the impedance to neutral of one of a pair of conductors parallel to a conducting and/or magnetic plate is given by $Z - Z_1$, where Z is the eddy-current self-impedance of the cable with plate return and Z_1 the mutual impedance between this circuit and that comprising the second cable with plate return. The problem is similar to that of an overhead-line circuit with earth return, which has been investigated mathematically by Carson,† and his values for Z and Z_1 may be taken, provided the current density on the side of the plate remote from the cables is negligible. This assumption is correct if $2h\sqrt{\alpha}$ is greater than 10, where h is the distance of the conductors from the plate and $\alpha = 4\pi\sigma\mu\omega$, σ and μ being respectively the conductivity and the permeability of the plate in c.g.s. units. Even if $2h\sqrt{\alpha}$ is not much greater than unity the error in the above assumption is not serious. The losses so evaluated are, however, far lower than those observed, since no allowance is made for hysteresis. The latter may be taken into account by expressing the permeability as $\mu e^{j\phi}$, and it can be shown that this multiplies the losses by $\cos\frac{1}{2}\phi + \sin\frac{1}{2}\phi$. For mild steel ϕ is of the order of 45°, and the increase in the losses due to hysteresis will therefore be about 30 %. The increments of resistance and reactance have been calculated in this way for cables spaced 6 in. apart, and are shown in Fig. 13. The agreement with observation is as close as can be expected in view of the difficulty in assigning correct values to α and ϕ, and serves to show that hysteresis losses are a determining feature and that further increase in the thickness of the steel would not increase its effect since the losses occur only at or near the surface adjacent to the conductors. It is to be noted that the theory put forward explains the slow change observed in impedance increment with spacing between the conductors unless the latter are very close to the steel.

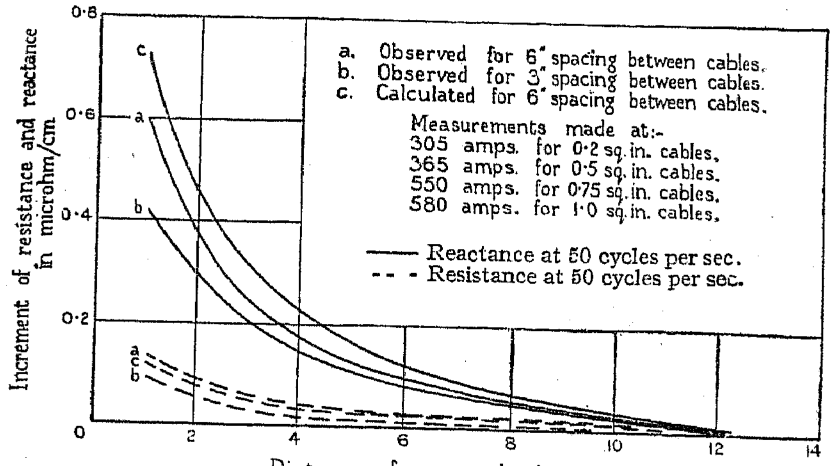


Fig. 13.—Increase of resistance and reactance due to steel plate when sheaths are insulated. Single-phase systems.

The foregoing theory can be applied to devising means for ameliorating the effects due to adjacent metalwork. Normally the losses are, to a first approximation, inversely proportional to the square root of the product of permeability and conductivity, and unless special constructional methods can be adopted mild steel compares favourably with other material, as illustrated in Table 3. In such cases as switch and busbar cubicles, however, it might be possible to reduce the losses by interleaving steel with highly conducting material or preferably attaching to the steel bands of copper running parallel to the cables and joined at the ends, in order to give a low-resistance path to the eddy currents while retaining the high magnetic properties of the steel.

Table 3

RESISTANCE INCREMENT DUE TO ADJACENT METAL PANEL. (AXIAL SEPARATION OF CONDUCTORS = 38 CM. DISTANCE OF CONDUCTORS FROM PANEL = 15 CM.)

Material of panel	Resistance increment as percentage of value for mild steel
Mild steel	100
Cast iron	300
Aluminium	285
Non-magnetic steel	1 230
Interleaved steel and aluminium ..	79
Mild steel with bonded copper bands ..	28

When the sheaths are bonded the core current is partly shielded by the sheath current, thus reducing the inducing field in the steel, but, at the same time, the presence of the steel increases the magnetic flux between the cables so that the sheath currents are greater and the energy loss in the sheaths is increased by the presence of the steel. The net effect is an increase in resistance and a corresponding decrease in reactance owing to the shielding effect. These two effects are shown in Fig. 14. It is observed that, owing to the presence of two opposite effects on the resistance, as explained, the sheath loss (increment of resistance on bonding sheaths) is not affected by the steel until the cables are close to it, when the loss rises rapidly. The decrease of reactance on bonding the sheaths is affected by the steel at greater distances. The absolute values for these quantities depend on the sheath resistance and its dimensions, so that they vary with the size of cable. Accordingly, the value of a theoretical calculation does not justify the complexity involved. The variation of cable rating follows to a large extent the variation of sheath loss. The former can, in fact, be calculated from the latter by the methods given in Appendix II, but only to a limited accuracy on account of the thermal effect of the steel and proximity effect in the cable cores.

---

* See Bibliography, (5).

† *Ibid.*, (6).

In an untransposed 3-phase system in one plane, the measured increment of resistance of a phase due to alternating current is given by $(R_c + R_A)$, where R_c is the resistance due to skin effect and core and sheath proximity effects, and R_A is the resistance due to phase transfer of power.* This latter term, in the absence of steel, is 0·76 microhm per cm. for the outer cables, being positive for phase I (the leading phase) and negative for phase III, while for the middle cable it is zero. Correcting the measurements in this way it is found that the resistance is the same in both outer cables and its increment in the presence of steel is greater than that of the middle cable, as shown in Fig. 15.

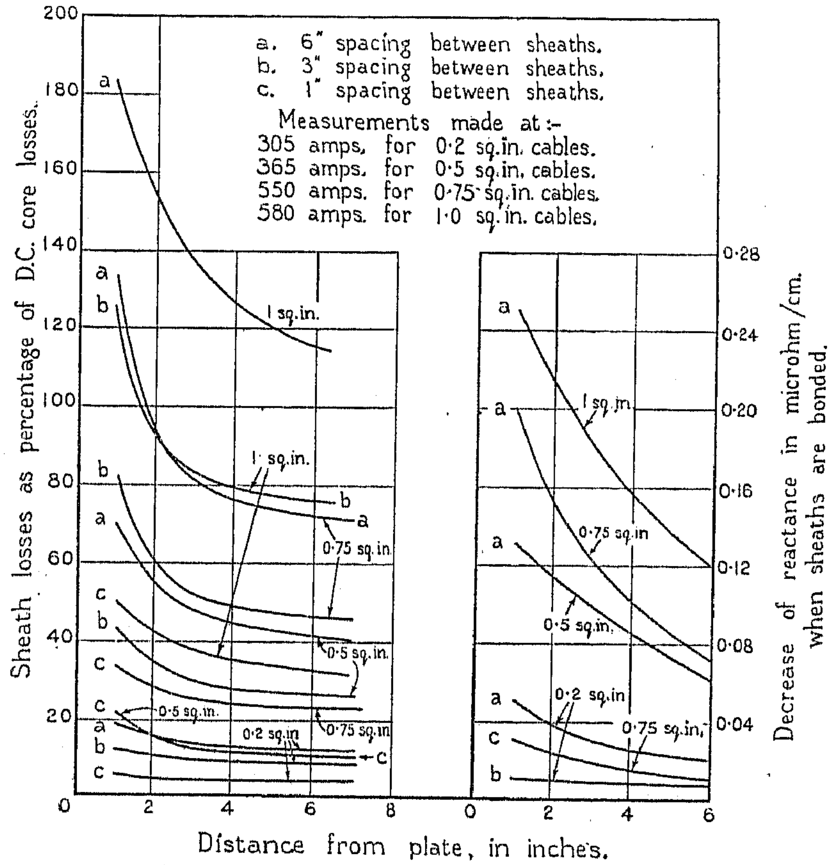


Fig. 14.—Effect of bonding sheaths in presence of steel plate. Single-phase systems.

The absolute values in microhms per cm. are independent of the size of the cable, except that the loss is higher in larger cables when very close to the steel. Further, the mean loss per phase due to the steel agrees approximately with the values for single-phase systems and arises from the same cause as previously computed. Accordingly the difference between the outer and the middle cables is to a large extent due to asymmetry in the phase transfer of power, increased by the presence of the steel and causing a transfer of power from the middle to the outer phases. In addition, the proximity effects are different in the middle cable. Apart from this, 3-phase and single-phase systems should give nearly the same results since the quantity Z_1 defined above is small, while Z is not affected by the change from single-phase to 3-phase.

The reactance X in the 3-phase case may be shown in the same way to be given by—

$$X = \lambda \log (s/2b) + X_c + X_A$$

where $s =$ spacing, $b =$ radius of core, $\lambda = 0{\cdot}216$ microhm per cm. at 50 cycles per sec. in absence of steel, and $X_A =$ phase transfer of reactive power (1·45 microhms per cm. at 50 cycles in absence of steel). X_A is positive for phase I, negative for phase III, and zero for the middle cable. X_c is the internal inductance, which was found to be approximately unaffected by the steel. Accordingly Fig. 16 shows the increase in the first and third terms due to steel separately. This increase is independent of size of cable and of phase except very near the steel, when the outer cables have a greater reactance, while that of smaller cables is greater than that of larger. As with the resistance, the mean increment of reactance per phase is approximately the same as that for a single-phase system, in agreement with theory. The asymmetry already referred to is illustrated in the difference between X_A for phases I and III near steel.

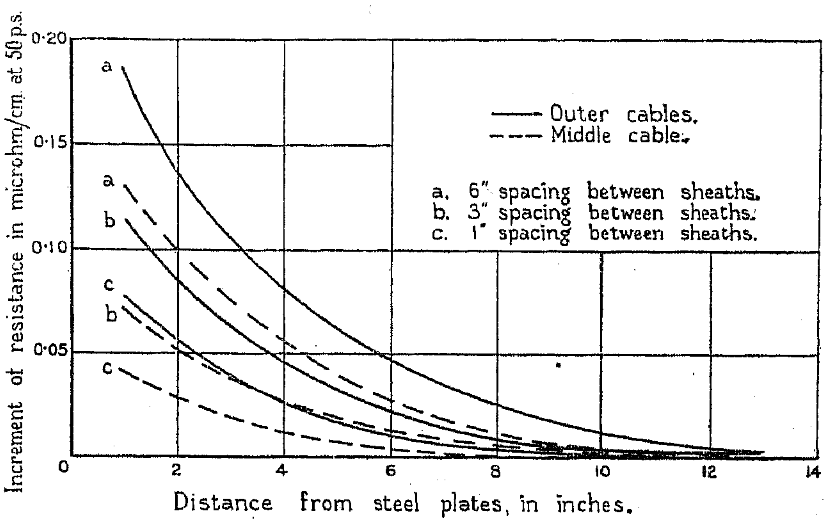


Fig. 15.—Increase of resistance due to proximity to steel in 3-phase systems.

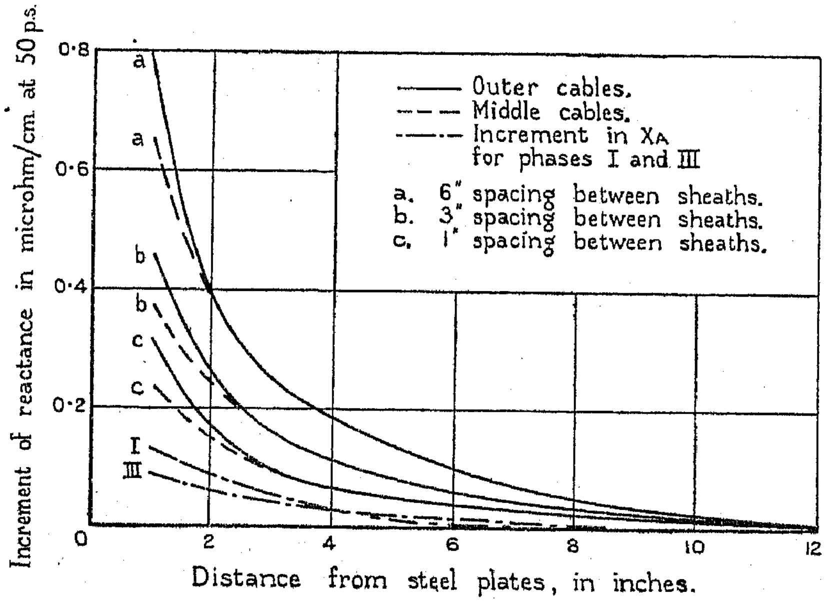


Fig. 16.—Increase of reactance due to proximity to steel in 3-phase systems.

Figs. 17A and 17B show the effect of steel on the increase of resistance due to bonding the sheaths, i.e. the apparent sheath losses. The true sheath losses involve the measurement of the sheath currents, since otherwise a transfer of power between the sheaths is included. This transfer causes the minimum effect observed in phase III, since the transfer of power decreases the apparent impedance of phase III and increases that of phase I. Nevertheless it is clear that the cable of phase I will be hottest with large cables. The increase in sheath losses due to steel mainly determines the decrease of carrying capacity. The decrease in reactance on bonding the sheaths is shown for 1-sq. in. cables in Fig. 18. The phase transfer of power which increases the apparent sheath losses of phase I tends to compensate the flux due to the sheath currents in that phase. Accordingly the reactance of phase I may increase slightly on bonding the sheaths. For small cables the effect on the reactance of bonding the sheaths is small.

---

* See Bibliography, (4).

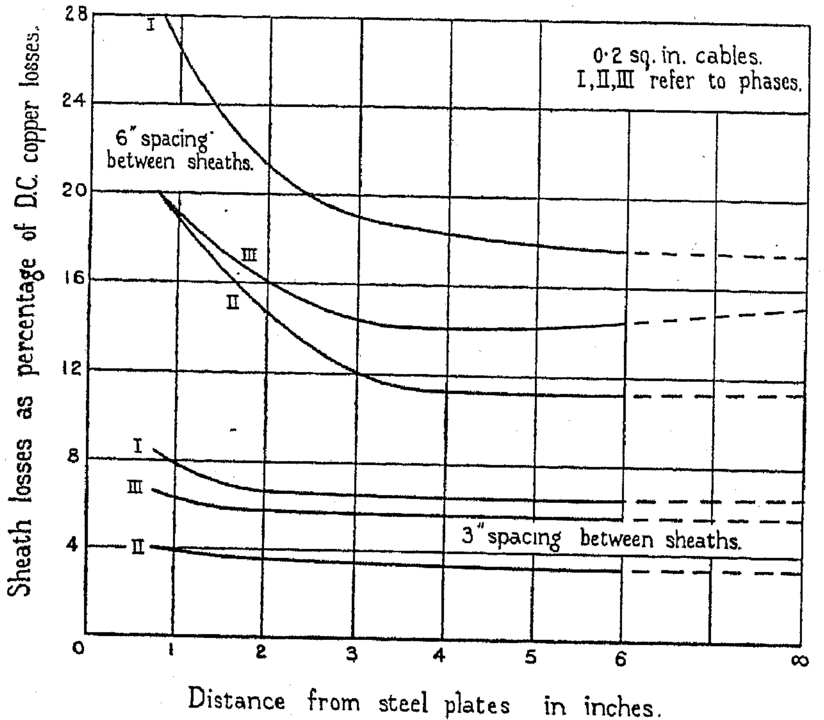


Fig. 17A.—Effect of steel on sheath losses. Three-phase systems.

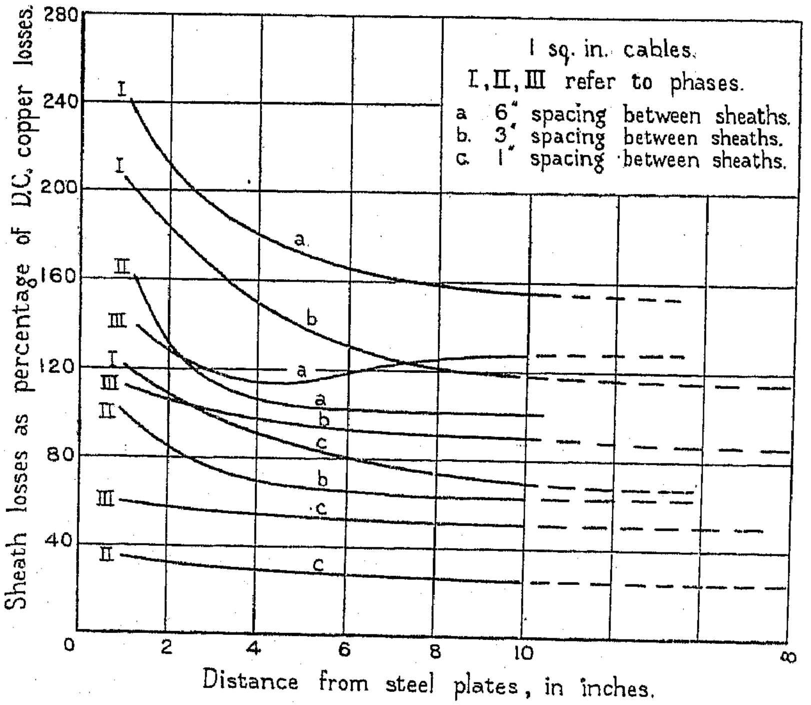


Fig. 17B. —Effect of steel on sheath losses. Three-phase systems.

(iv) Effect of current density on impedance.

The effect of current density over the range tested was small, the increment of resistance due to the steel decreasing with increase of current while the reactance increased. The amount of the latter was about 1 per cent per 100 amperes when the cable was as close as possible to the steel plate. The decrease of added resistance due to alternating current in the same conditions was negligible for insulated sheaths except for 1-sq. in. cables, when it was about 1 per cent per 100 amperes. For bonded sheaths, the decrease was about 1 per cent per 100 amperes for 0·2-sq. in. cables, rising to 2 per cent per 100 amperes for 1-sq. in. cables. These figures refer to the range 2/3 to full load, which was the range covered in all these tests.

(v) Armoured or magnetically-screened cables.

Although single-conductor armoured cables are not employed with alternating current, some tests were made on a 0·75-sq. in. armoured cable to determine how far armouring, conduits, etc., would screen the effects of the steel plate. It was found that only a slight increase in losses occurred near the steel, and it was concluded that the impedance of cables screened by steel armouring or conduits would be substantially unaffected. The carrying capacity of the armoured cables was increased by about 10 per cent when the cables were actually resting on the steel plate, so that the rating of cables may be materially increased by supporting them close to a steel plate or bulkhead if the magnetic effects are screened in a simple manner.

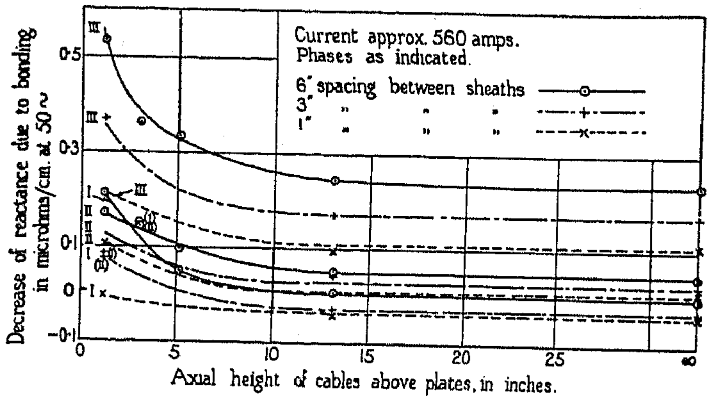


Fig. 18.—Effect of steel plates on decrease of reactance due to bonding sheaths for 1·0-sq. in. cables (3-phase).

(b) Cables Passing Through Steel Structures

(i) Single cable passing through steel plate.

This condition is rare but sometimes occurs in ships and in generating stations and substations, particularly in switch houses, where the return lead or remaining phases may be widely separated. Accordingly a test was made on a cable loop about 20 ft. square, one side of which was formed by a 0·75-sq. in. single-conductor unarmoured cable passing through a steel plate 3 ft. × 4 ft. 6 in. × 0·4 in. thick, by means of a circular central hole in which the cable was supported centrally by a wooden bushing. The cable was laid in a tunnel kept at a reasonably uniform temperature.

Apart from its effect in impeding free convection currents from the cable, the steel plate had no important effect on the mean or local temperature of the core when the sheaths were insulated. Thus this aspect may be neglected under general working conditions, the reduction in current rating being less than 5 per cent. When the sheaths were bonded to form a complete loop the sheath at the steel plate was hotter than the steel, so that no reduction of carrying capacity is to be anticipated by direct effect of the steel. However, with so large a cable loop the sheath currents were approximately 39 per cent of the core current, with a corresponding reduction in current rating.

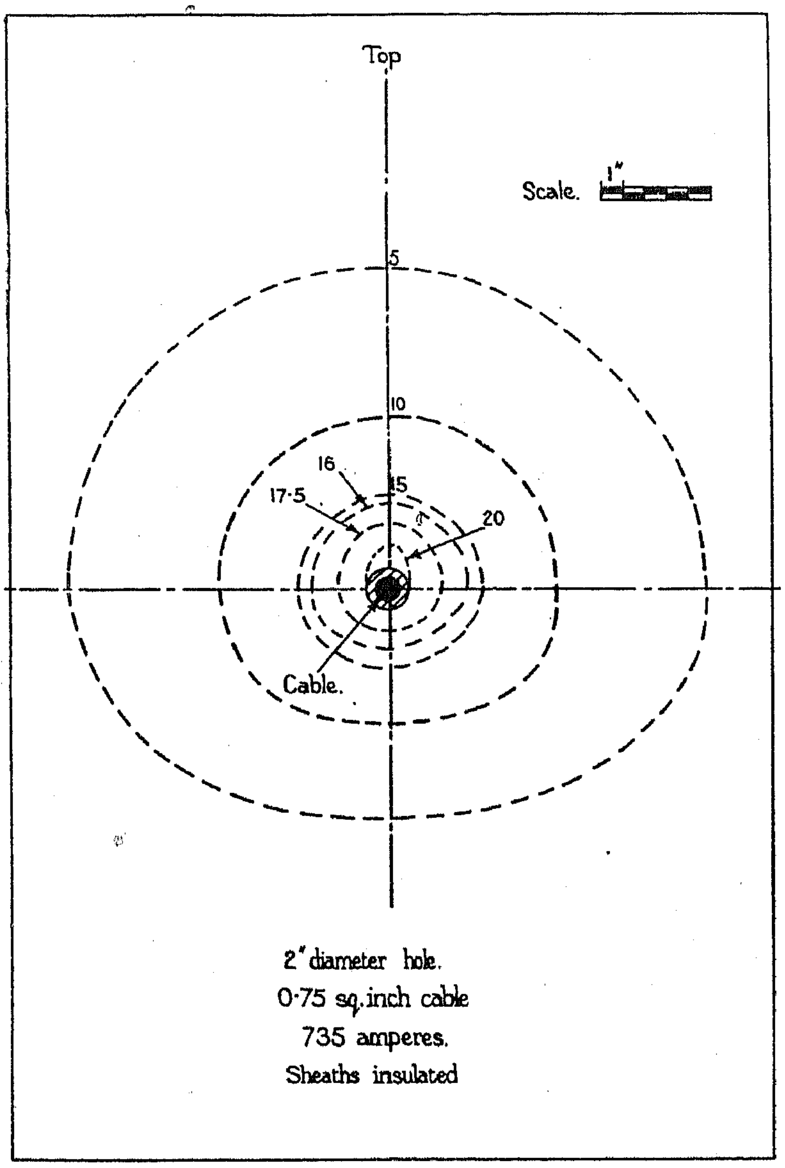


Fig. 19.—Isothermals in steel plate.
Numbers on curves give temperature-rises in deg. C.

Apart from the sheath currents, which may be eliminated by a suitable impedance bonding, the main interest lies in the heating of the steel. Fig. 19 shows the temperature distribution in the plate, the isothermals being distorted from circular form by the vertical convection currents. The condition illustrated is that giving the highest temperature-rise in the steel, viz. 80 per cent of the core temperature-rise. With a 6-in. hole and insulated sheaths the maximum temperature-rise of the steel was 30 per cent of the core temperature-rise, while with bonded sheaths the screening effect of the sheath current reduced these values to 30 per cent and 10 per cent for 2-in. and 6-in. holes respectively.

The results of the tests are given in Table 4.

Thus it is observed that, if a 6-in. diameter hole is allowed, the steel will not heat to any serious degree, and even if the hole is reduced to 2 in. diameter the temperature will only be important on account of possible contact with materials of poor heat-resisting properties or very low ignition temperatures, or where a small differential expansion might have serious results, as in some types of reinforced structures. Apart from this the passage of a single cable carrying alternating current through steel plates and walls does not appear to involve very serious disadvantages.

(ii) Three cables passing through steel plate.

Tests were made with a 3-phase system of single-conductor cables up to 1-sq. in. conductor section passing through the plate already described by holes of $2\frac{1}{8}$ in. diameter at axial spacings of $4\frac{5}{16}$ in. and $7\frac{5}{16}$ in., the cables being held centrally in the holes by wooden bushings. As in the single-cable tests, the current-carrying capacity of the cables, as determined by the mean core temperature over the whole length, was unaffected by the presence of the steel. Further, there was no indication of any appreciable local heating where the cable passed through the plate except under the worst conditions tested, viz. 1-sq. in. cables with sheaths insulated, when local heating may reduce the carrying capacity (based on the "hot spot" temperature-rise) by 10 per cent at an axial spacing of $4\frac{5}{16}$ in. or by less than 5 per cent at an axial spacing of $7\frac{5}{16}$ in. The other factor which may influence the overall rating is the voltage drop. The results indicated that in this respect,

Table 4

Test Results on Cable Loop, showing Effect of Steel Plate on Paper-Insulated Lead-Sheathed Cables

Condition	Insulated sheaths				Bonded sheaths			
	Current for temperature-rise of 27·7 deg. C.	Total losses* as percentage of d.c. loss	Reactance at 50 cycles per sec.	Sheath voltage per ampere of core current	Current for temperature-rise of 27·7 deg. C.	Total losses* as percentage of d.c. loss	Reactance at 50 cycles per sec.	Sheath current per ampere of core current
	amperes		ohm	volt	amperes		ohm	ampere
No plate	775	109·4	0·00903	0·00793	435	447	0·00740	0·385
Plate with 6-in. hole	745	121·0	0·00910	0·00803	435	453	0·00738	0·386
Plate with 2-in. hole	745	125·4	0·00909	0·00802	435	471	0·00729	0·393

* Including copper loss.

while the plate considerably increased the apparent resistance of the cables, the overall impedance of a 20-ft. run was only increased by approximately 10 per cent for 1-sq. in. cables, with sheaths insulated, at an axial spacing of $7\frac{5}{16}$ in. The effect was less for smaller cables and at narrower spacings, while bonding the sheaths also reduced the effect of the plate. The absolute value of the loss in the steel is mainly a function of the thickness of the plate, the geometrical configuration of the system, and the cable current. It varies only slightly with size of cable. Accordingly impedance effects are more important with larger cables where the normal impedance is less.

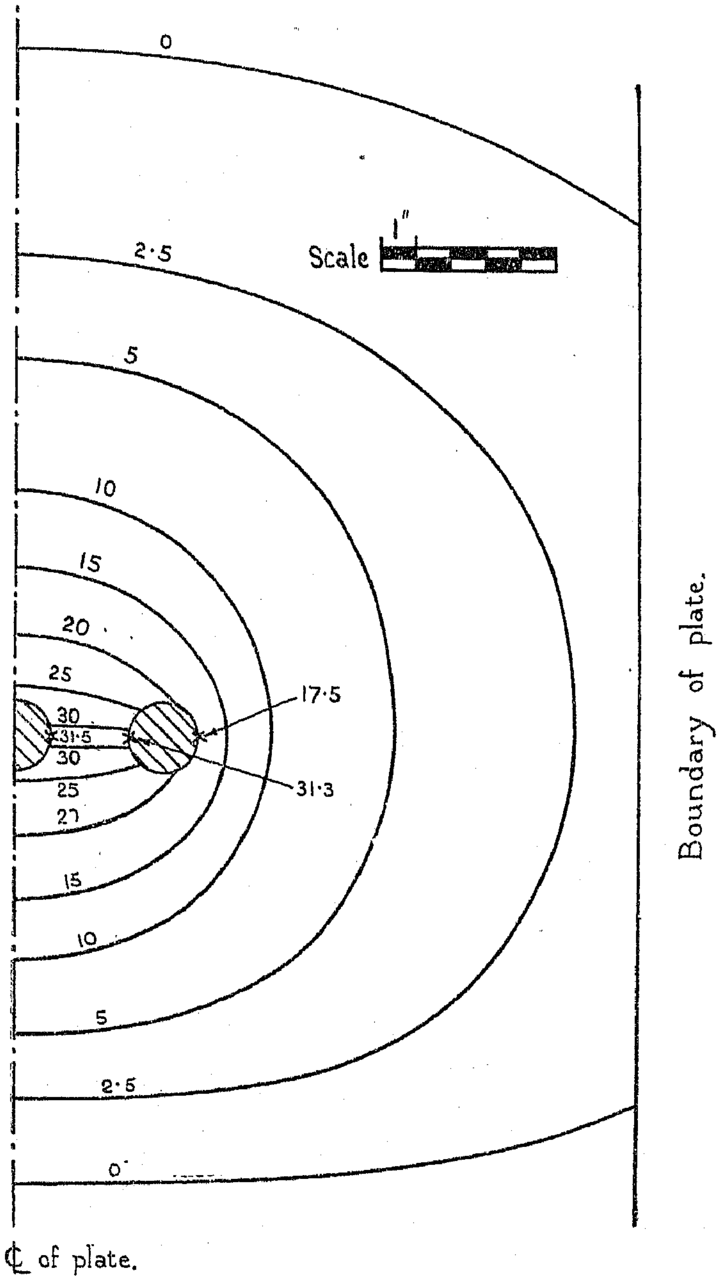


Fig. 20.—Isothermals in steel plate. 1-sq. in. cables, $4\frac{5}{16}$ in. axial spacing. Sheaths bonded, 630 amperes.

Numbers on curves give temperature-rises in deg. C.

The heating in the steel itself was a rather more serious matter. The maximum temperature-rise of the plate occurred at the edge of the central hole, as shown in Fig. 20, and was unaffected by bonding the cable sheaths. From Figs. 21 and 22 it is seen that the maximum temperature-rise of the plate was of the order of twice the mean core temperature-rise for 1-sq. in. cables, but of the same order as the core temperature for 0·5-sq. in. cables. The losses by convection and radiation were determined for the zones of roughly uniform temperature given by the isothermals, utilizing the formula—

$$P = k_1\theta^{5/4} + k_2\theta \text{ watts per cm}^2$$

where θ = temperature-rise, k_1 and k_2 = convection and radiation constants respectively, the approximation in the second term being valid for small temperature-differences. Assuming $k_1 = 0\cdot002$ and $k_2 = 0\cdot0006$ (black-body), the equivalent resistance due to the plate was found to be 0·00018 ohm while the measured increment of resistance was 0·00025 ohm. In view of the difficulty of allowing for heat dissipated through the cables, the difference in the values is not considered excessive.

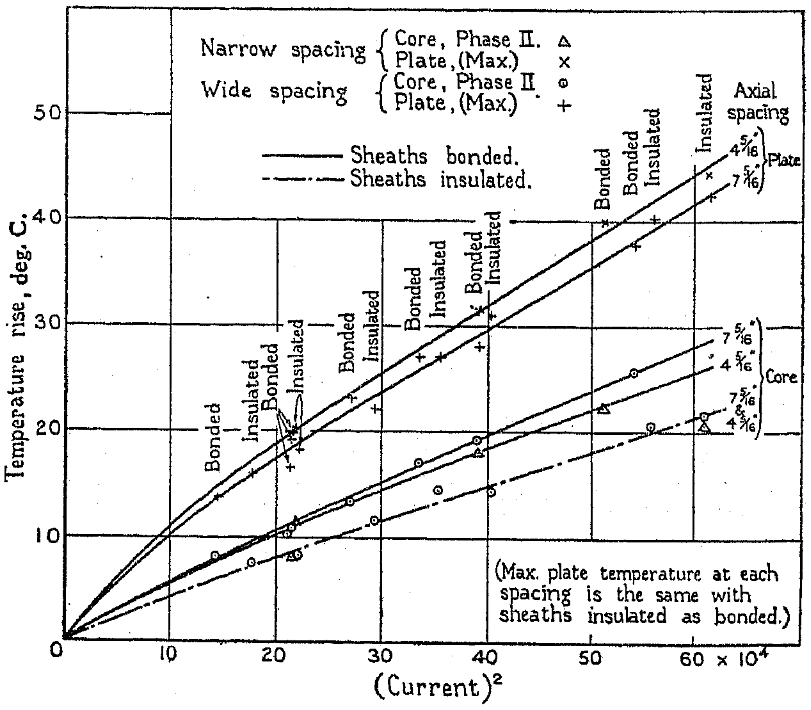


Fig. 21.—Three single-core 1-sq. in. cables passing through steel plate.

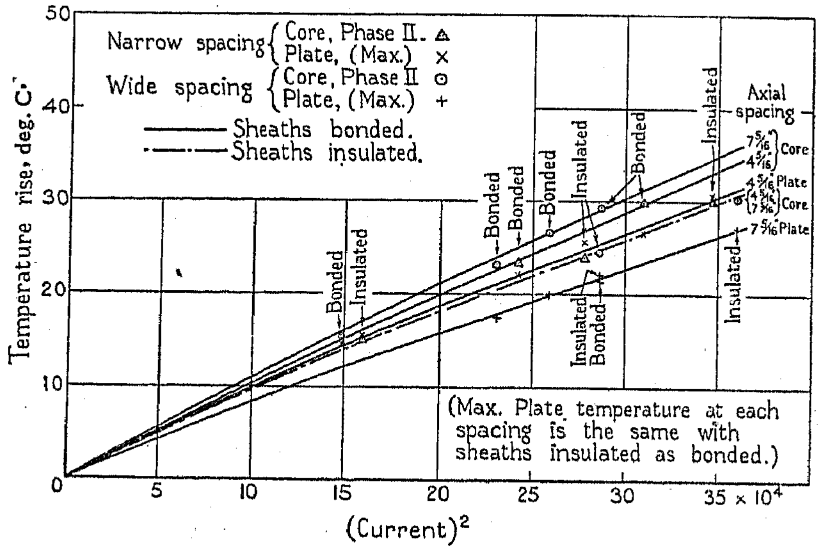


Fig. 22.—Three single-core 0·5-sq. in. cables passing through steel plate.

In the worst case with the 1-sq. in. cables it is possible for the maximum temperature-rise in the steel to reach nearly twice that of the cable core. Outside the hottest zone a temperature gradient per inch of 20 per cent of the core temperature-rise may exist.

Although this would not usually constitute a fire risk yet the temperature gradient might conceivably cause structural damage due to differential expansion, although, in such a case, the thermal conductivity of the surrounding medium would alleviate the temperature-rise. To minimize such trouble it is suggested that at least $\frac{3}{8}$ in. clearance should be allowed between lead sheath and steel, that the sheaths should be bonded and that, where possible, the axial spacing should be not less than 6 in. or preferably 9 in. for cables above 0·5 sq. in. The first condition is fulfilled by the use of non-magnetic glands or bushings, the second is normal practice, while the third may be omitted in inconvenient cases without serious trouble. The problem does not arise where a non-magnetic gland plate is used in addition to non-magnetic glands. Smaller cables may be run in parallel for each phase where this economizes space.

(iii) Cables passing through steel-rod structures.

Research on cables passing through concrete with steel-rod reinforcement is still in hand, but a preliminary study suggests that there again the problem is one applying only to large cables and that, as with the steel plate, the main risk is that of differential expansion. For example, a frame 4 in. square formed of $\frac{3}{8}$ in. diameter steel rod was supported on a 0·75-sq. in. cable and surrounded by material of low thermal conductivity. The temperature-rise of the steel rod was again nearly twice that of the cable core.

Table 5

TEST RESULTS ON RUBBER-INSULATED CABLES IN CONDUITS

Size of cable, and stranding	Size of conduit for two cables	Three cables per conduit (vertical)			Four or six cables per conduit		
		Size of conduit	Rating as percentage of that for two cables per conduit		Number of cables and size of conduit	Rating (d.c. or balanced-a.c. loading) as percentage of that for two cables per conduit	
			D.C. or balanced a.c. loading	Unbalanced a.c. loading		Vertical conduits	Horizontal conduits
	in.	in.	amperes	amperes			
3/·029 (0·002 sq. in)	$\frac{5}{8}$	—	—	—	6, 1 in.	71	67
3/·036 (0·003 sq. in.)	$\frac{5}{8}$	—	—	—	6, 1 in.	67	69
7/·029 (0·0045 sq. in.)	$\frac{3}{4}$	—	—	—	4, 1 in.	—	79
7/·044 (0·01 sq. in).	$\frac{3}{4}$	1	87	77	4, 1 in.	81	80
	1	1	86	75	4, 1 in.	79	—
7/·052 (0·0145 sq. in.)	1	—	—	—	4, $1\frac{1}{4}$ in.	81	79
7/·064 (0·0225 sq. in.)	1	$1\frac{1}{4}$	85	72	—	—	—
	$1\frac{1}{4}$	$1\frac{1}{4}$	83	71	—	—	—
19/·052 (0·04 sq. in.)	$1\frac{1}{4}$	—	—	—	4, $1\frac{1}{2}$ in.	79	81
19/·083 (0·1 sq. in.)	2	2	83	62	—	—	—

(c) Conclusions

When cables carrying alternating current are run along a steel structure or a structure reinforced by steel, the carrying capacity is reduced (except for small cables run very close to the steel), and the impedance is increased. In severe cases, such as with steel plates, these effects are of such magnitude as to require taking into account in the determination of current rating and voltage-drop. The effects diminish with decrease of size of cable and increase of distance from the steel, and are not increased by increase of thickness of the steel plates, provided a certain thickness (usually fairly small) is exceeded.

When single-conductor cables pass through steel structures the carrying capacity based on core temperature and the voltage-drop are rarely affected to an important extent. However, the steel structures may be heated by large cables to temperatures which, while not often constituting a fire risk, may be disadvantageous owing to differential expansion in the structure.

Attention may also be drawn to the large reduction in carrying capacity which occurs with bonded sheaths when the phases are widely separated even over a short length.

(3) CABLES IN CONDUITS AND CHASES

(a) Small Rubber-Insulated Cables in Steel Conduits

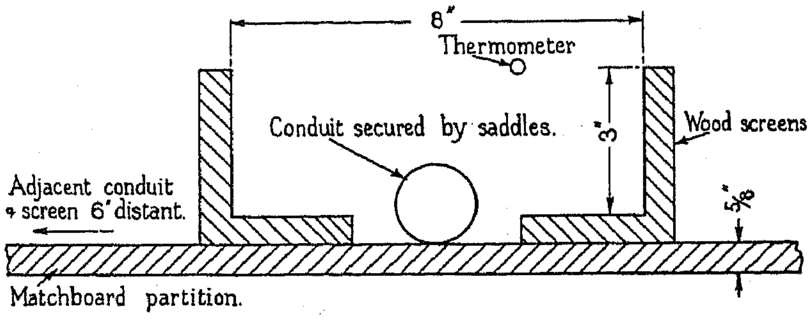
(i) General.

In this method of running cables, one of the most popular for domestic wiring systems, modern conditions involve in many cases a considerable reduction in current rating as compared with that permitted in the former I.E.E. Tables of carrying capacity, which were based mainly on two cables carrying direct current in a conduit or chase buried in plaster. A material increase in impedance is also often involved in present conditions. Tests were accordingly made on new rubber-insulated cables (taped and braided) supplied by C.M.A. firms to B.S.S. No. 7—1926,* which were run in vertical and horizontal steel conduits in groups of 2 to 6 cables carrying single-phase or 3-phase alternating current or direct current. The tests made are summarized in Table 5.

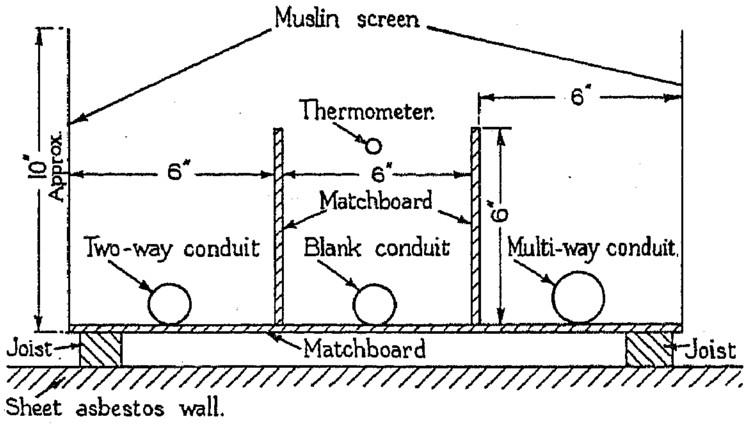
The conduits (welded, screwed, and black-enamelled) complied substantially with B.S.S. No. 31—1923 and were about 10 ft. long. For vertical tests they were installed as shown in Fig. 23. The horizontal conduits were mounted by stirrups on wooden joists in a cable tunnel. Generally two conduits were joined by a screwed union to form a run of 20 ft. These conditions were intended to give the most severe conditions normally encountered in practice. The a.c. and d.c. impedances were measured with a Campbell–Larsen potentiometer. The core temperatures were measured with thermocouples and by change of resistance, and the surface temperatures of the cables by resistance thermometers and thermocouples, as also were the internal conduit temperatures. The external conduit temperatures were measured with thermocouples, and the ambient air temperatures by thermometers. Tests made inside a blank vertical conduit failed to show any signs of a "chimney effect," the temperature at any given level agreeing to within 0·2 deg. C. with the ambient air temperature at the same level.

---

* See note on B.S.S. Nos. 7 and 480, on page 497.



(a) First series of tests.



(b) Second series of tests.

Fig. 23.—Mounting and screening of vertical conduits.

(ii) Current-carrying capacity.

As illustrated in Figs. 24 and 25, the temperature-rise is proportional to the square of the current, although for these small temperature-rises it is difficult to distinguish between different indices. The temperatures in a horizontal conduit were uniform along the length; in a vertical conduit the bottom was about 5 per cent cooler than the top, the carrying capacity being therefore based on the temperature-rise at the top of the conduit. Plugging the ends had no appreciable effect.

Direct comparison upon the same conduits showed that for the range of cables tested there was no difference between the temperature-rises for direct current and balanced alternating current, single-phase or 3-phase. If, however, the alternating current is not balanced, the heating is greater, owing to the losses in the conduit. Tests were made with an arbitrary form of unbalance in which three cables in a conduit were supplied with single-phase alternating current in series. Unbalanced currents will usually be rare but are liable to occur during change-over from direct current to alternating current. A considerable reduction in carrying capacity would then result.

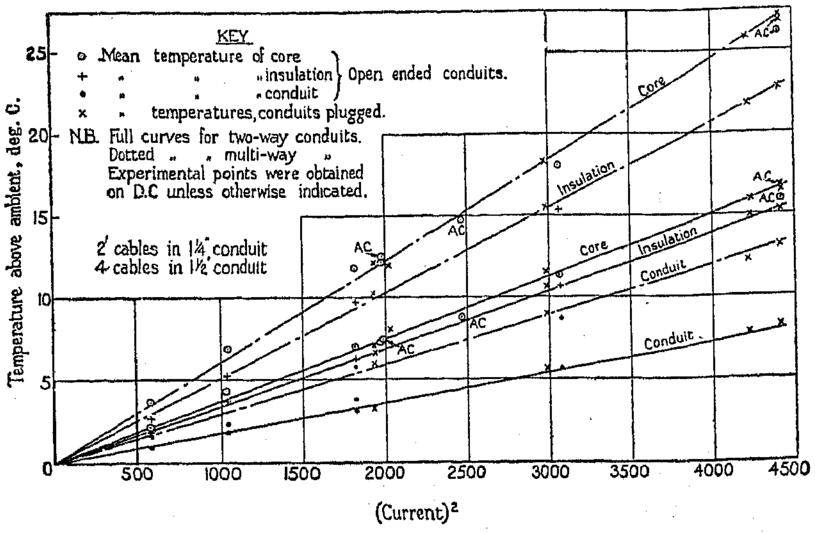


Fig. 24.—Heating curves for 19/·052-in. cables (vertical).

Fig. 26 shows the variation of carrying capacity based on a temperature-rise of 11·1 deg. C. or 20 deg. F. with size of cable for the basic case of two cables in a conduit of appropriate size.* For any other temperature-rise θ deg. C. which may be permitted, the values shown must be multiplied by a factor $(\theta/11\cdot1)^{0\cdot5}$. The rating for vertical conduits is about 4 per cent less than for horizontal conduits.

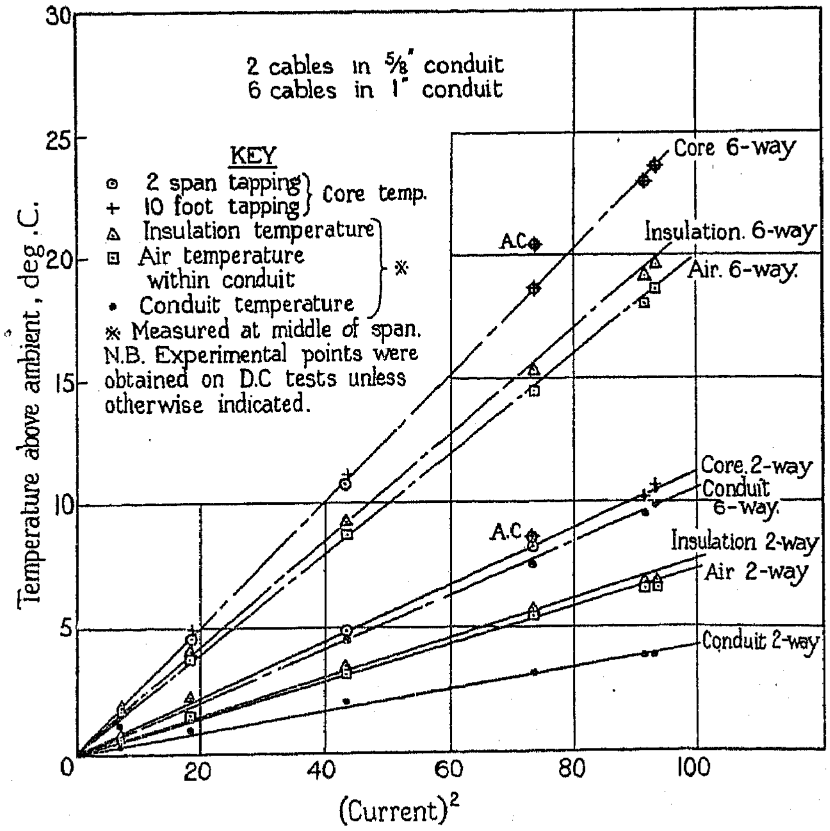


Fig. 25.—Heating curves for 3/·029-in. cables (horizontal).

Table 5 gives the ratings for 3, 4, and 6 cables in a conduit, expressed as a percentage of those for two cables of the same size.

---

* The curves follow the law $I = kA^{0\cdot59}$, where I = carrying capacity, A = conductor section in sq. in., k = 370 for vertical or 385 for horizontal conduits.

If the thermal resistance per core did not change with number of cables in the conduit, then the rating for n cables would be $\sqrt{(2/n)}$ of that for 2 cables. Actually the thermal resistance decreases with number of cables, owing to increase in the number of heat paths in parallel and increase in size of conduit, so that the reduction shown in Fig. 27 is less. Analysis of the heat path showed that the thermal resistance external to the conduit was of the order of one-half the total, the thermal resistance of the insulation being about 15 per cent for 2 cables and decreasing to about 5 per cent for 6 cables. The thermal dissipation from horizontal conduits agreed with theory, details of which are given in Appendix II. Fairly wide tolerances are permissible on the thermal resistivity of the dielectric. Again, the thermal dissipation from a conduit does not change rapidly with size, so that there is some freedom in the choice of a suitable conduit. Direct tests showed that a change in diameter of ¼ in. altered the rating by only 2 or 3 per cent.

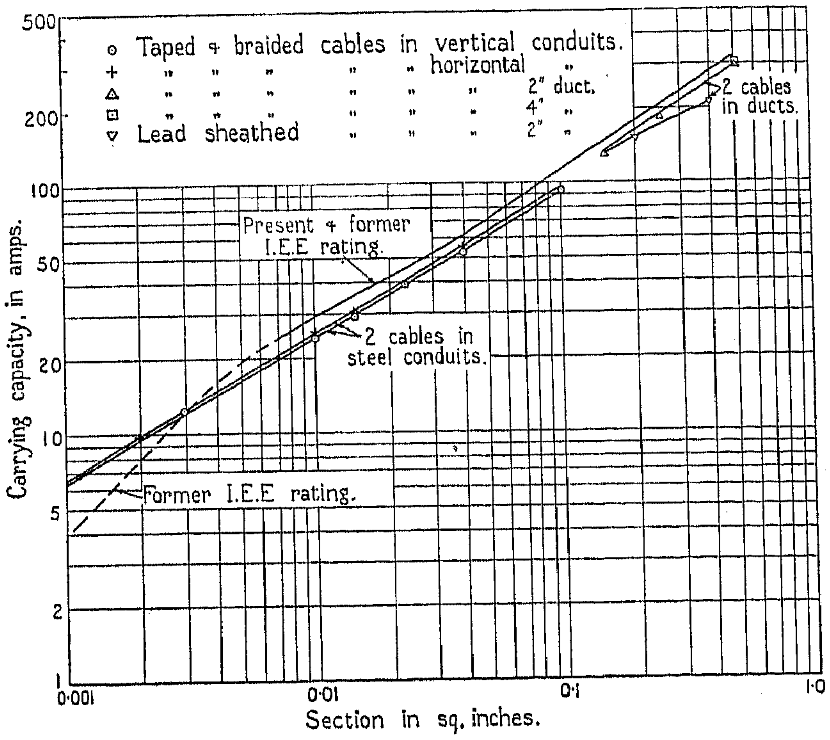


Fig. 26.—Carrying capacity of cables in conduits and ducts.

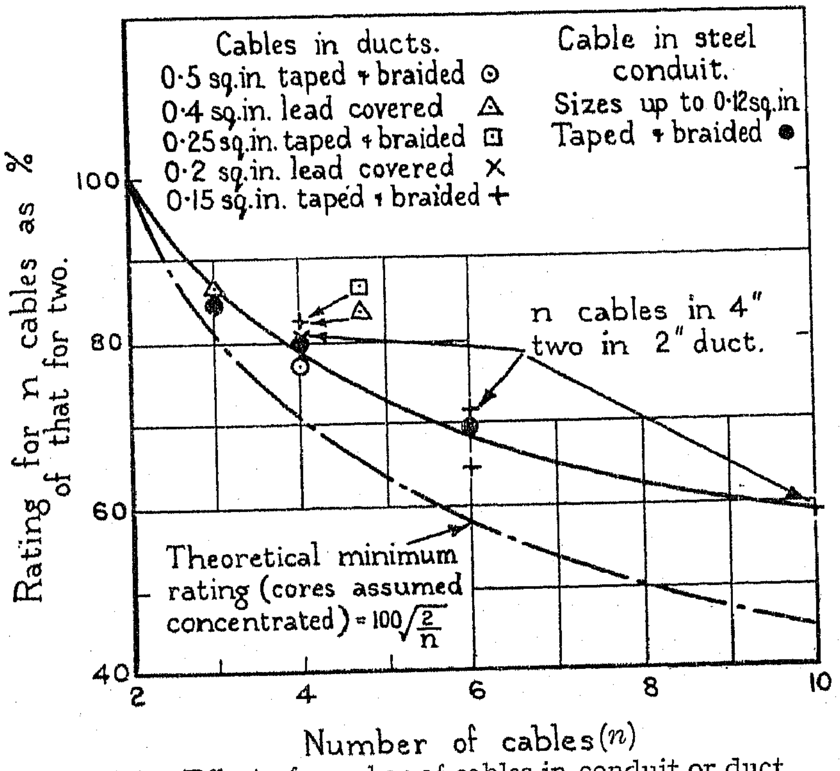


Fig. 27.—Effect of number of cables in conduit or duct on rating.

(iii) Impedance.

The a.c. impedance of cables in a conduit does not change appreciably with current, and provided the a.c. circuits were all either single-phase or balanced 3-phase the number of such circuits was found to have only a negligible effect on the impedance. Fig. 28 shows the impedance as compared with the d.c. resistance. The effect is negligible for cables smaller than 0·02 sq. in. but rises to about 12 per cent for 0·1-sq. in. cables. Knowing the properties of the steel of the conduit and the disposition of the cables within, it is possible to compute the impedance from the formulae of the mathematical analysis of such problems already mentioned.* While the properties of the steel are rather uncertain the disposition of the cables is more important. Accordingly, two curves are shown in Fig. 28, one assuming the largest possible separation and the other assuming the cables are as close as possible and central in the conduit. The increased impedance is due mainly to reactance, the increased resistance due to steel losses rarely exceeding about 1 to 2 per cent of the copper losses, in agreement with the temperature-rise experiments. Test results agree better when the widest separation is assumed.

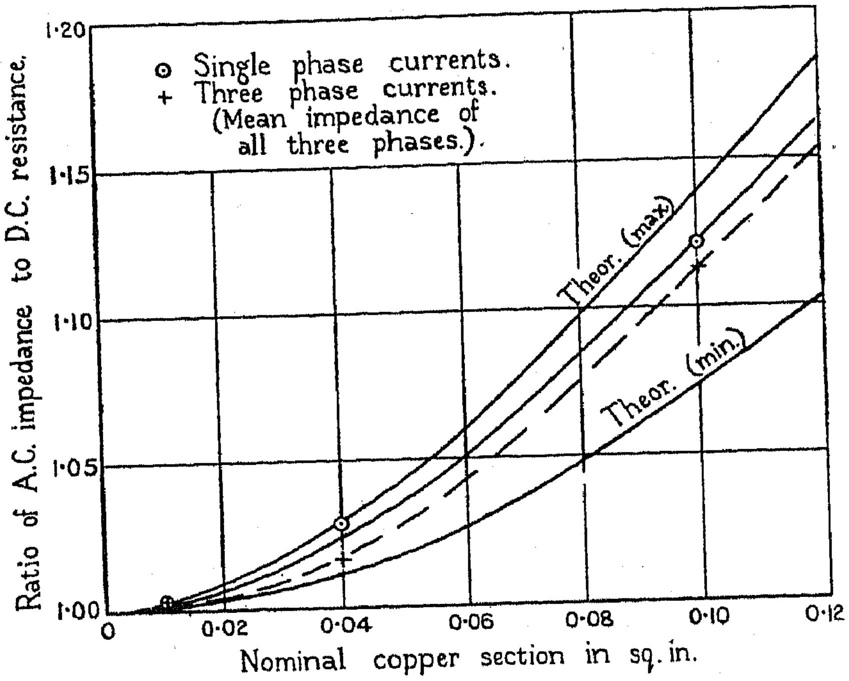


Fig. 28.—Impedance of cables in steel conduits.

(b) Cables in Horizontal Ducts

Large cables (0·15–0·5 sq. in. section) are frequently run in buildings grouped in non-metallic ducts which are sometimes buried in plaster. Tests were made on cables run in asbestos ducts of rectangular section resting on the floor, and the temperature-rise was found to vary as the 1·7th power of the current, indicating convection to be the more important mode of dissipation of heat. As in the case of similar cables run free in air, the current rating corresponding to a temperature-rise θ, different from the value θ_0 permitted in the Tenth Edition of the Wiring Regulations, may be calculated by multiplying the values given therein by $(\theta/\theta_0)^{0\cdot54}$ within the proper limits stated in (1) (*d*) above. The mutual heating is the same as in steel conduits, Fig. 27, showing that the reduction of rating with increase in number of cables is the same for ducts as for conduits. Fig. 26 shows also that for taped and braided cables the rating differs little from the extrapolated law for smaller similar cables in steel conduits, except that the rating is somewhat higher. The ratings of these cables for direct current and for alternating current are the same within 2 per cent up to 0·5-sq. in. section, and this is also true for the lead-covered cables up to 0·4-sq. in. section, although the sheaths were bonded. It was also shown that the electrical balance of the system was immaterial provided all cables were equally loaded. Thus three cables loaded in series gave the same rating as with a balanced 3-phase load.

---

* See Bibliography, (5).

Tests with ducts of 4½ in. width but with either 2 in. or 4 in. depth showed that the rating increased with size of duct but that the effect did not exceed 5 per cent. The comparison between groups of different numbers of cables is made on the assumption of a constant size of duct.

The a.c. impedance can be calculated from theory as in other cases, but it is necessary to assume a small average separation of about 2 mm. between sheaths owing to the difficulty of ensuring contact throughout the length. Sheath losses, skin effect, and proximity effects are small with cables of the sizes under consideration.

It may be noted that the deductions drawn for the rubber-insulated cables as regards the equality of d.c. and a.c. loading, size of duct, and group reduction-factor, apply also to paper-insulated cables. The difference between the present current ratings and the original I.E.E. ratings corresponds roughly to the effect of burying the ducts in plaster or concrete, which increases the rating by about 10 per cent, in agreement with the earlier work of Melsom and Booth.[*]

(c) Small Lead-Sheathed Cables

Cables of this type are frequently run horizontally one above the other directly against a vertical wall, or a bulkhead. Such installations are included in the present section since they often form an alternative to cables in conduits. In order to simulate the most severe case the cables were run directly against a double asbestos wall with wooden battens, by means of brass saddles or metal clips. The sheaths were bonded at the points of support and were in contact throughout their length. The methods of measurement were the same as in previous tests.

No difference was found in the rating as between alternating current and direct current, the core temperature being proportional to the square of the current in both cases. Table 6 shows the ratings for two cables run together, determined for a temperature-rise of 27·7 deg. C. for paper-insulated and 11·1 deg. C. for rubber-insulated cables, compared with the I.E.E. ratings and with the ratings given in Section (3) (*a*) for two rubber-insulated cables in a conduit. For any temperature-rise θ, different from the value θ_0 permitted in the Tenth Edition of the Wiring Regulations, the ratings given in Table 6 must be multiplied by a factor $(\theta/\theta_0)^{0\cdot5}$. As is to be expected, the rubber-insulated ratings are rather higher when lead sheaths are used than with a conduit system, while the new determinations for paper-insulated cables also give higher values.

Table 6

LEAD-SHEATHED CABLES

Size of cable	Insulation	Experimental rating[*]	Conduit rating[*] (rubber-insulated)	I.E.E. rating[*]
		amperes	amperes	amperes
7/·044 (0·01 sq. in.)	Rubber	29·6	26·2	31
7/·052 (0·0145 sq. in.) ..	Paper	61	—	57
19/·052 (0·04 sq. in.)	Paper	118	—	104
19/·052 (0·04 sq. in.)	Rubber	67	57	64
19/·072 (0·075 sq. in.) ..	Paper	170	—	157

[*] Based on a core temperature-rise of 11·1 deg. C. and 27·7 deg. C. for rubber-insulated and paper-insulated cables respectively, two cables being run together in each case.

Since the thermal resistance of the conduit to air is no longer interposed in the heat path for all the cables, the effect of a multiple row of lead-sheathed cables is less than with conduits. The lowest cables are cooler but the middle and upper cables have about the same temperature, and the rating is based on the upper cables. It was then found that with a group of 4 cables the rating was reduced to 87 per cent of the value for two cables, and with a group of 6 (direct current, 3 circuits of single-phase alternating current, or 2 circuits of 3-phase alternating current) the rating was 83 per cent. The same ratings may be used for cables on steel bulkheads in ships since the steel will, if anything, increase the rating owing to superior thermal dissipation.

The impedance of the cables can be calculated from the already-established theory for sheath losses and line constants. It is only in the largest sizes considered in this Section that the a.c. impedance differs materially from the d.c. resistance. The effect on the impedance of a steel bulkhead in ships follows the laws enunciated in a previous Section.

---

[*] See Bibliography, (1). A similar observation applies to steel conduits, except that the effect of burying in plaster is rather greater. In view of this the ratings have not been reduced in the Tenth Edition of the Wiring Regulations.

Table 7

BARE COPPER RODS

Diameter of rod	Rating based on temperature-rise of:—				
	55·5 deg. C.		30 deg. C.		30 deg. C. (Melsom and Booth)*
	Single-phase (2 rods)	3-phase (3 rods)	Single-phase (2 rods)	3-phase (3 rods)	Free in air
in.	amperes	amperes	amperes	amperes	amperes
$\frac{3}{8}$	230	230	170	170	159–170
$\frac{5}{8}$	430	400	340	320	330–352
1	800	700	650	590	648–691

* *Journal I.E.E.*, 1924, vol. 62, p. 909. The values quoted here are 20–25 per cent lower than those given in the paper itself, which describes tests made on rods painted dull black.

(d) Bare Conductors in Chases, and Rubber-Insulated Cables Connected Thereto

The installation of bare conductors in ducts for the purpose of electrical distribution to the various floors or sub-circuits is a recent development in building practice, and it was accordingly necessary to deal with this in the Tenth Edition of the Wiring Regulations. Tests were therefore made on common sizes of hard-drawn unpainted copper rod $\frac{3}{8}$ in., $\frac{5}{8}$ in., and 1 in. in diameter to determine the current rating when mounted in a vertical chase (11 in. wide, 5 in. deep), using wooden cleats at 5 ft. intervals which gave an axial spacing of 3 in. As anticipated the temperature-rise followed the convection law, being proportional to the 1·6th power of the current. The ratings based on temperature-rises (measured at the hottest part of the rods) of both 55·5 deg. C. (100 deg. F.) and 30 deg. C. above ambient outside the chase, are given in Table 7.

Table 8

TEMPERATURE-RISES OF RUBBER-INSULATED CABLES CONNECTED TO BARE RODS

Distance from clamp	Cable unloaded		Cable loaded	
	Single-phase	3-phase	Single-phase (37 amperes)	3-phase (32 amperes)
in.	deg. C.	deg. C.	deg. C.	deg. C.
1	37	38	40	40
3	28	30	34	34
6	19	19	25	24
9	8	8	15	14
12	3	3	10	8
18	<1	<1	7	6

Owing to the large temperature-rise allowed for these rods, 55·5 deg. C. as compared with the 11·1 deg. C. allowed for the rubber-insulated cables often connected to them by clamps, the insulation of such cables is exposed to an excessive temperature near the clamp, although the latter reduces the temperature of the rod in its neighbourhood. As an example, the temperature distribution along 7/·052-in. rubber-insulated cables connected to $\frac{5}{8}$-in. copper rods loaded for a maximum temperature-rise of 55·5 deg. C. is given in Table 8. Results with other combinations were similar, and it was deduced that if special measures were taken as regards the insulation within 15 in.* of the clamps, the rubber-insulated cables would not be exposed to excessive temperatures outside this zone.

(e) Cables in Long Vertical Chases

Although certain regulations such as those of the L.C.C.† enact, in some circumstances, that a cable duct shall be stopped at any point where it passes through a fire-resisting wall or floor, so as to prevent the passage of fire or smoke from one section of the duct to another, yet cases occur where existing or special shafts are used for the passage of rising mains. This leads to the possibility of the collection of hot air towards the top of the shaft or duct accompanied by temperatures in excess of those normally encountered.

---

* This distance would be reduced if a higher temperature-rise than 11·1 deg. C. were permitted for rubber-insulated cables.

† L.C.C. "Regulations and Rules with regard to Structural Requirements as to Lighting, Heating, Electrical, Ventilating and Mechanical Installations—Places of Public Entertainment."

The problem is one of the variation of ambient temperature, and tests were made on an asbestos chase 60 ft. long, 18 in. wide, and either 9 or 16 in. deep, containing six 0·5-sq. in. paper-insulated plain lead-sheathed cables fixed therein by wooden cleats arranged asymmetrically so as to touch one side of the chase and to leave a 2-in. gap on the other side. The axial spacing of the cables was 2 in. except that for the centre pair, which was 3 in. Fig. 29 shows the temperature variation for a chase stopped at the top only. Fig. 30 shows the variation when a chase is stopped at the top and also 10 ft. from the bottom, corresponding to a fire-resisting floor, while Fig. 31 shows the variation when a chase is open throughout. The temperature gradient, as is to be expected, is steepest near an open bottom or closed top end, the intermediate gradient being less and not so much affected by the ends, being of the order of 0·1 to 0·2 deg. C. per foot at 472 amperes under all test conditions. The proximity of cool air causes a slight fall of temperature near the top, if open. As with ducts and chases generally, the temperature-rise is proportional to the 1·6th power of the current (following the convection law), while the depth of chases of the size considered was not found to be material.

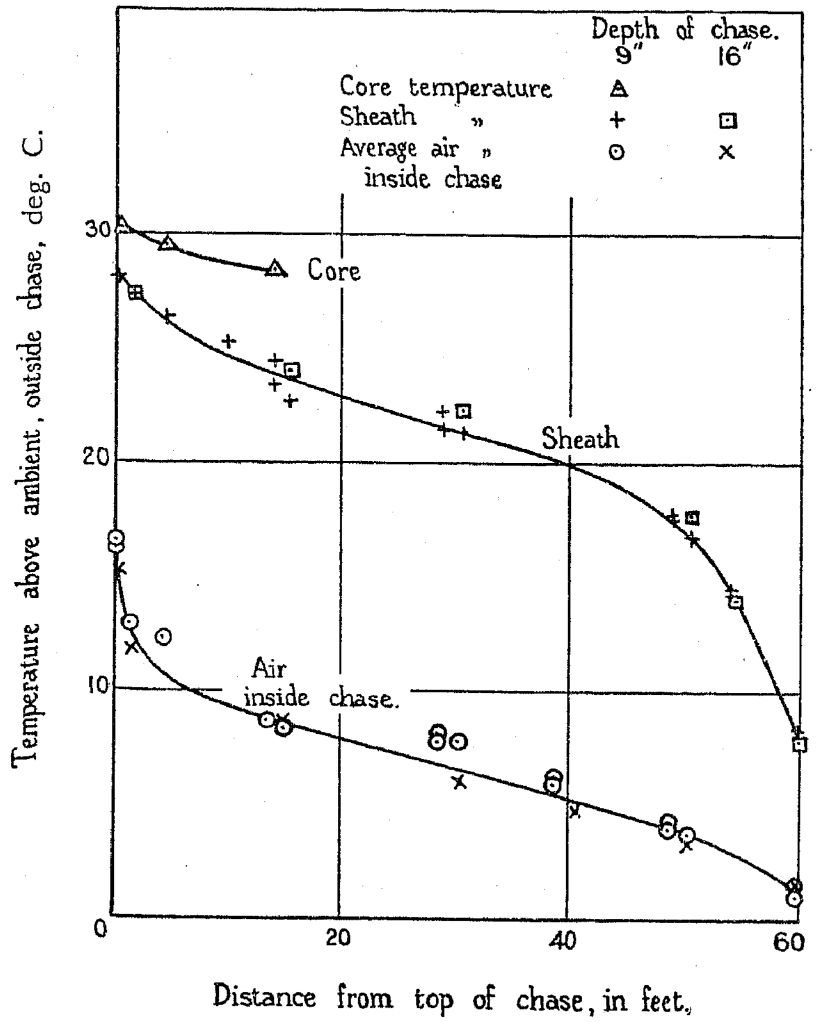


Fig. 29.—Temperature variation along a chase stopped at the top only. Current, 472 amperes.

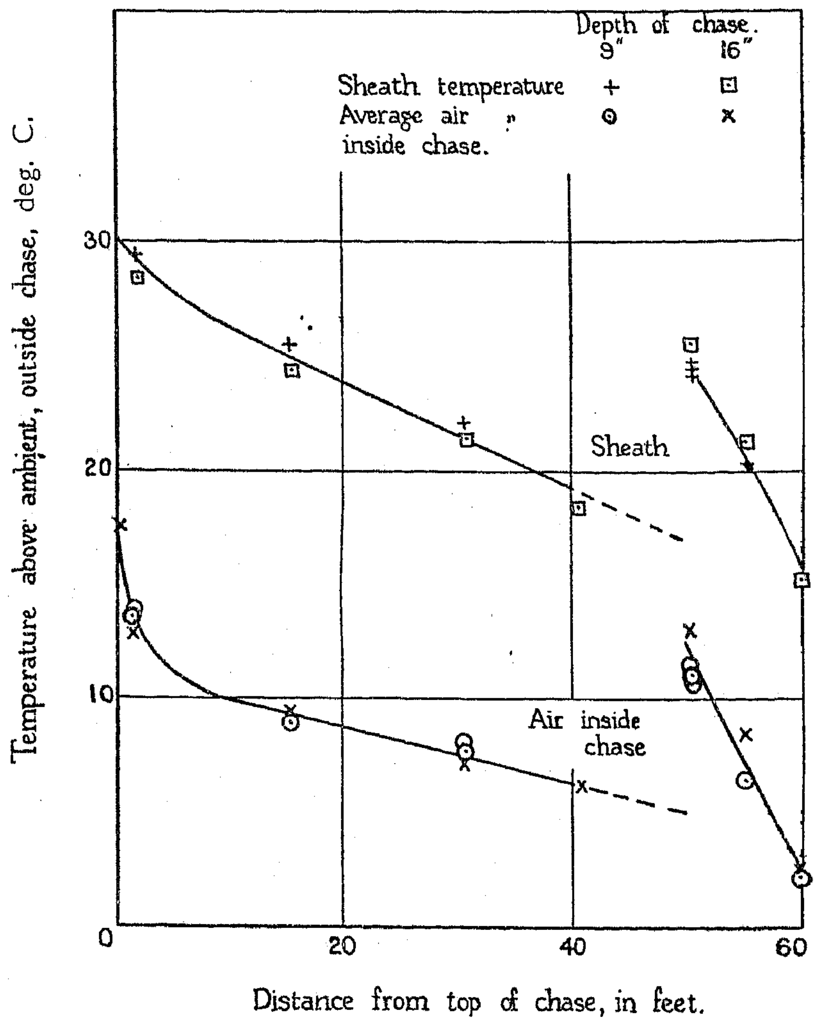


Fig. 30.—Temperature variation along a chase stopped both at the top and 10 ft. from the bottom. Current, 472 amperes.

The temperature variations both along the sheath and in the air inside the chase increase with but are not proportional to the length. If a stopping is introduced the temperature immediately below it is considerably increased, but the temperatures above are not greatly affected. Accordingly, in considering the effect on the rating, the maximum temperature variation along the

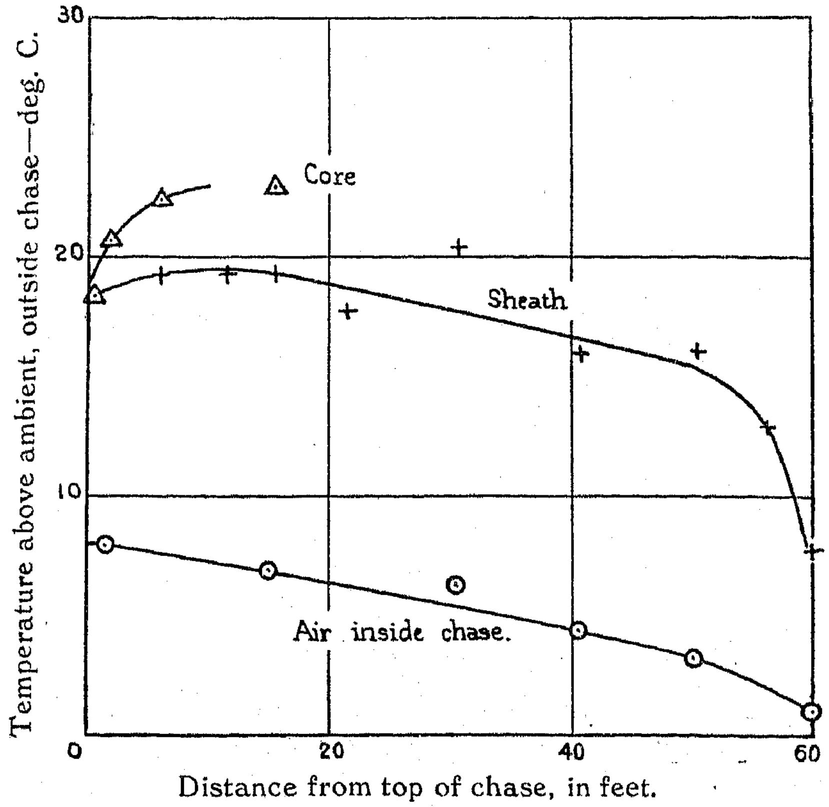


Fig. 31.—Temperature variation along a chase open throughout. Current, 472 amperes.

sheath can be taken and it can be assumed that the effective ambient temperature is raised by this amount. In the present case this variation did not exceed 15 deg. C., neglecting the extreme lower end.

(f) Conclusions

(i) The former I.E.E. current ratings based on the work of Melsom and Booth give in some instances (surface conduits and ducts) higher values than those determined experimentally, and in other instances (surface wiring systems) lower values than those found experimentally. Accordingly, since the conduit and duct test conditions were somewhat severe, the original figures may be said to have been confirmed as an average for conduit, casing, duct, or troughing systems of wiring and also for surface or "bunched and open" systems. The differences of other cases from this average are relatively small.

(ii) Where more than two cables are so run a reduction factor must be applied according to the number. These factors do not vary greatly as between the different systems so that it is possible to adopt, as in the Tenth Edition of the Wiring Regulations, general average reduction factors for 4, 6, and 10 cables (or their equivalent), viz. 80 per cent, 70 per cent, and 60 per cent respectively. The reduction factor for six cables may also be applied to obtain the current rating of one 3- or 4-core cable from that of two single-core cables of the same size.

(iii) For the sizes considered, namely, up to 0·5 sq. in. for 2 or 4 cables, up to 0·25 sq. in. for 6 cables, and up to 0·15 sq. in. for 10 cables, the d.c. and balanced-a.c. ratings may be taken as the same. With steel conduits a lack of balance in an a.c. system may cause a material reduction in the carrying capacity.

(iv) The carrying capacity based on temperature-rise may be deduced theoretically, and is in reasonable agreement with experiment; but, owing to variation in conditions, it is unwise to rely upon theoretical results. The impedance or voltage-drop is in satisfactory agreement with theory in the absence of ferrous material and also in its presence, subject to certain assumptions.

(v) Bare copper rods may be run at a higher temperature than insulated cables, and have higher ratings. If rubber-insulated cables are connected thereto, excessive heating of the insulation need only be anticipated within a short distance of the joint.

(vi) The I.E.E. Wiring Regulations allow a margin of safety as regards ambient temperature which would cover the variation in temperature in vertical chases. The loss of this margin of safety cannot generally be recommended, and a reduction in carrying capacity may have to be considered on this account. The use of intermediate stoppings, as prescribed by some authorities, is not necessarily a cure.

(vii) The carrying capacity of cables in conduits, chases, ducts, on walls, etc., may be expressed approximately as $kA^{0\cdot59}$ amperes, where A is the cross-section in sq. in. and k is a factor depending on the method of installation and the number and nature of the cables.

(viii) The current rating corresponding to a core temperature-rise θ may be calculated from the current which will produce any other core temperature-rise θ_0, by multiplying the latter by a factor $(\theta/\theta_0)^n$. For cables of less than 0·1 sq. in. installed under any condition, $n = 0\cdot5$, while for larger cables n may be taken as 0·54, provided that θ/θ_0 is not less than 0·56 nor greater than 1·8.

ACKNOWLEDGMENTS

The authors wish to record their appreciation to the E.R.A. for permission to publish this paper, and to the Committees of the E.R.A. and I.E.E. under whose direction the work was carried out. Finally, the authors would thank Mr. E. B. Wedmore, the Director of the E.R.A., for his advice and help in the preparation of the paper.

BIBLIOGRAPHY

(1) S. W. Melsom and H. C. Booth: *Journal I.E.E.*, 1911, vol. 47, p. 711.
(2) A. H. M. Arnold: *ibid.*, 1929, vol. 67, p. 69.
(3) R. A. Brockbank and J. K. Webb: *ibid.*, 1929, vol. 67, p. 337.
(4) E. B. Wedmore, P. D. Morgan, and S. Whitehead: *ibid.*, 1929, vol. 67, p. 359.
(5) S. Whitehead: *Philosophical Magazine*, 1931, vol. 11, p. 897.
(6) J. R. Carson: "Wave Propagation in Overhead Wires with Ground Return," *Bell System Technical Journal*, 1926, vol. 5, p. 539.
(7) A. H. M. Arnold: *Journal I.E.E.*, 1935, vol. 77, p. 49; also E.R.A. Report F/T55; *ibid.*, 1935, vol. 76, p. 299; also J. C. Costello: *ibid.*, 1936, vol. 79, p. 595.

APPENDIX I

Impedance of Single-Conductor Cables

The resistance R of a single-conductor cable is given by

$$R = R_0(1 + y + y_1 + y_2) + R_A + R_X$$

where—

R_0 = d.c. resistance;

y = skin effect, for which values have been given by Arnold;[*]

y_1 = proximity effect, for which values have been given by Arnold[*] (which may be modified by presence of steel);

y_2 = ratio of sheath losses to copper losses, for which values have been given by Arnold[†] and by Wedmore, Morgan, and Whitehead,[‡] the two methods giving the same results;

R_A = phase transference of power,[†] [‡] which is modified by steel as shown in this paper;

R_X = loss in neighbouring bodies such as steel plate or conduit, and may be determined by the method indicated by Whitehead.[§]

The reactance X is similarly given by

$$X = X_c + X_0 + X_A + X_X - X_B$$

where—

X_c = internal self-inductance, given by Wedmore, Morgan, and Whitehead;[‡]

---

[*] See Bibliography, (7); the proximity effect for 3 cables, based on Costello's analysis, has been given by Arnold in an unpublished E.R.A. Report.

[†] See Bibliography, (2).

[‡] *Ibid.*, (4).

[§] *Ibid.*, (5).

X_0 = normal inductance between thin conductors in same position;

X_A = phase transference of reactive power, given by Arnold* and by Wedmore, Morgan, and Whitehead,† which may be modified by the presence of steel as shown in this paper;

X_X = inductance due to the presence of magnetic material such as steel plate or conduit, which may be determined by the method indicated by Whitehead.‡

X_B = decrease of inductance due to bonding the sheaths,*† which may be modified by steel as shown in this paper.

APPENDIX II

Theoretical Determination of Current-Carrying Capacity

It has been shown that usually where there is an energy loss in a neighbouring body, the resultant heating does not greatly affect the temperature-rise of the cable itself except in special circumstances.

Thus if G_0 is the thermal resistance of the core to sheath or covering and if G' is the thermal resistance from the outside to the ambient medium, then the temperature-rise θ of the core is given by—

$$\theta = G_0R_0(1 + y + y_1)I^2 + G'R_0(1 + y + y_1 + y_2)I^2 \quad . \quad (1)$$

If I is the rated current and θ the standard temperature-rise—

$$I = \left[\theta/R_0\left\{G_0(1 + y + y_1) + G'(1 + y + y_1 + y_2)\right\}\right]^{1/2} \quad . \quad (2)$$

G_0 may easily be calculated from standard formulae. For an isolated conductor free in air—

$$G' = 1/(k_1\theta^{1/4} + k_2) \quad . \quad . \quad . \quad . \quad (3)$$

where k_1 is the convection constant for cylinders and k_2 is the constant for radiation and conduction, being 0·0006 watt per cm.² for black-body radiation alone.

In the case of a cable with sheath losses and appreciable thermal resistance of the insulation—

$$G' = 1/(k_1\theta_s^{1/4} + k_2)$$

and

$$\frac{\theta}{\theta_s} - 1 = \frac{G_0}{G'}\left(1 - \frac{y_2}{1 + y + y_1 + y_2}\right) \quad . \quad . \quad (4)$$

where θ_s is the temperature-rise of the cable surface.

For n cables in a conduit or duct, G' must be replaced by nG'.

Some particular cases can be simplified. For cables run in air on cleats the thermal dissipation is given approximately by $k\theta_s^{5/4}$, where k is a constant depending on the size of cable, the number of cables, and their relative disposition. Accordingly—

$$G' = 1/\left(k\theta_s^{1/4}\right) \quad . \quad . \quad . \quad . \quad . \quad (5)$$

Only a small error will result in G' for a much larger error in θ_s, so that it is possible to employ general mean values for θ_s in determining G', whence the rating can be found from equation (2). For a core temperature-rise of 28 deg. C., θ_s may be taken as 22·5 deg. C., and for a core temperature-rise of 11 deg. C. as 8·5 deg. C. The constant k has been determined for a wide range of cable types and conditions in some work carried out subsequent to the main investigations described in the present paper. For two cables run along a wall k varies between 0·0004 and 0·00051 watt per cm.² per deg. C., and between 0·00037 and 0·0005 watt per cm.² per deg. C. for three cables similarly run, the range of sizes being from 1·16 to 4·5 cm. overall diameter.

In the case of rubber-insulated cables, there is good agreement between the measured and calculated values of current ratings. The results of the tests on lead-sheated, paper-insulated cables show that there is appreciable difference in the current ratings with the sheaths in bright and black conditions, the measured ratings being approximately those for the bright condition.

Similar observations apply to cables in conduits where also y_2 is zero and y_1 and y may be neglected. Thus equation (2) becomes

$$I = \left[\theta/R_0(G_0 + nG')\right]^{1/2} \quad . \quad . \quad . \quad (6)$$

But

$$G' = G_1' + G_2' \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

where

G_1' = thermal resistance from cable to conduit, and
G_2' = thermal resistance from conduit to ambient air.

The quantity G_1' is variable, but as G_1' forms only about 30 per cent of the total a reasonable error is permissible. Experiments gave values ranging from 0·15 thermal ohm per cm. for 1½-in. conduits. This thermal resistance decreases to some extent as the number of cables is increased. The quantity G_2' is given by

$$G_2' = 1/(k_1\theta_c^{1/4} + k_2) \quad . \quad . \quad . \quad . \quad (8)$$

where θ_c, the temperature-rise of the conduit, may be taken as 5·5 deg. C. for vertical or 4·5 deg. C. for horizontal conduits, while k_1 and k_2 have already been defined. In practice, however, the empirical formula quoted in the footnote on page 510 gives better agreement with experiment than separate evaluation of the heat paths, since some of the variations of different portions of the heat path tend to compensate so as to give a smaller overall variation in the total temperature-rise. In addition the empirical formula is roughly valid for cables in ducts and chases.

It is important to note that, irrespective of the mode of installation, the ratio of the d.c. to the a.c. carrying capacity, excluding sheath losses, must be $\sqrt{(1 + y + y_1)}$. For all types of installations considered the sheath losses are always small for cables up to 0·1 sq. in., for which sizes y and y_1 are also negligible. Thus there is no difference between a.c. and d.c. ratings up to 0·1 sq. in. For cables without lead sheaths or run bunched together so that the sheath losses are small, the a.c. and d.c. ratings will only differ where $y + y_1$ is appreciable, namely for cables of 0·5 sq. in. and above.

[The discussion on this paper will be found on page 557.]

---

* See Bibliography, (2). † *Ibid.*, (4).
‡ *Ibid.*, (5).

CURRENT RATING OF CABLES FOR TRANSMISSION AND DISTRIBUTION

By S. WHITEHEAD, M.A., Ph.D., and E. E. HUTCHINGS, B.Sc.(Eng.), Associate Members.

[REPORT (REF. F/T117) OF THE BRITISH ELECTRICAL AND ALLIED INDUSTRIES RESEARCH ASSOCIATION.]

(*Paper first received 8th December, in revised form 21st December*, 1937, *and in final form 9th June*, 1938; *read before the* TRANSMISSION SECTION 19*th January*, 1938.)

SUMMARY

The developments in cable practice since the previous rating tables were issued* are treated from the aspect of their effect on current rating or carrying capacity, and the basis of the new rating tables is described. These tables are given, together with means for calculating the rating of cables installed in any of the usual modes.

LIST OF PRINCIPAL SYMBOLS

I = current (rating).
i = sheath current.
G = total thermal resistance.
G' = internal thermal resistance per core.
G_s = thermal resistance of serving, etc.
G_e = thermal resistance of soil.
G'_e = thermal resistance of soil with grouped cables.
G_A = thermal resistance of air.
G_d = thermal resistance of duct.
G_p = thermal resistance outside duct.
S = thermal capacity of cable.
S_e = thermal capacity of soil.
K = thermal resistivity of dielectric.
K_1 = thermal resistivity of serving, bedding, etc.
g = thermal resistivity of soil.
g_d = thermal resistivity of duct material.
D = diffusivity of soil.
d = diameter of cable over lead unless otherwise specified.
r = radius of conductor.
l = depth to axis of cable or duct.
r_e = overall radius of cable.
s = axial spacing of conductors.
c = axial displacement of conductor from axis of cable or axial displacement of cable from axis of duct.
R = resistance of conductor in ohms/cm at the temperature specified.
R_s = resistance of sheath in ohms/cm at the temperature specified.
R_A = resistance of armour in ohms/cm at the temperature specified.
$m = \omega / R_s 10^9$.
$m_1 = \omega / R_A 10^9$.
μ = effective permeability of armour.
η = hysteresis constant of armour.
y = skin effect increment.
y_1 = proximity effect increment.

LIST OF PRINCIPAL SYMBOLS—*continued*.

λ = sheath loss ratio.
λ_1 = armour loss ratio.
θ = current temperature.
θ_m = highest temperature in section.
θ_c = maximum permissible temperature-rise of core.
θ_s = maximum permissible temperature-rise of sheath or surface.
$k = \theta_s / \theta_c$
$k_1 = G'_e / G_e$
h = thermal dissipation constant in air.
t = time.
W = energy generated.
p = Heaviside's operator.
1 = Heaviside's unit function.

(1) GENERAL CONDITIONS

(a) Modern Developments

The work previously reported to The Institution,* and on which rating tables published by the E.R.A. were based, covered single-core and belted multi-core cables of the sizes then envisaged when loaded with direct current, although alternating current was nominally covered in addition. Since that time a considerable body of new data has been obtained and new methods introduced. The use of alternating current has involved the consideration of skin effect, proximity effect, sheath losses and armour losses, particularly with large cables. Although in effect the same standard value for the thermal resistivity of the soil is still employed, a large amount of new information, showing the variation with soil type, season, and depth, has been obtained and direct methods of measurement introduced. The thermal resistivity of the dielectrics has been fixed while the use of shaped cores and screened and S.L. type cables has involved a reconsideration of the internal thermal resistance. Certain specified types of intermittent loading are now recognized. Work on ducts has been extended and placed on a quantitative theoretical basis. A comprehensive set of thermal dissipation constants for cables in air has been derived. The effect of short sections of a cable-run has been considered.

The present report gives these new results, quoting also the previous work, such that the basis is described of the new rating tables, and means are given for calculating the rating of cables installed in a non-standard fashion. In general, results either well known or probably to be published later independently, are only briefly quoted, new work with which the authors have been particularly associated being given in more detail.

---

* See Bibliography, (1) and (2).

* See Bibliography, (1), (3), (4), and (5).

(b) Mode of Laying

Cables for long-distance transmission of power or forming part of a distribution network in an urban or rural district are laid underground. They may be buried direct in the soil or drawn into ducts, the former method effecting some saving in initial cost but the latter affording flexibility, e.g. phase isolation with single-core cables, and (if surplus duct-ways are provided initially) facility for expansion of the system without further excavation. For certain purposes, as in railway practice and for short external runs between large buildings, cables may be installed on racks or otherwise supported in air.

For the internal electrical equipment of buildings, the most common method of installation is by drawing cables into conduits or employing surface wiring systems, but wooden troughing is still used to some extent. Cables up to quite large sizes may be run free in air attached by cleats to the walls or rafters. In large modern buildings duct-ways and chases are often provided in the walls and floors for the wiring and for the installation of bare conductors for heavy current distribution. Internal installation will be referred to only briefly, however, in the present paper, having been fully dealt with elsewhere.*

(c) Temperature Limits

(i) Maximum Core Temperature.

The limiting core temperature is fixed by the maximum temperature at which the dielectric can be operated without deterioration over a long period. In the case of rubber-insulated cables, oxidation of the dielectric determines this limit, while for impregnated-paper cables it depends upon the temperature at which movement of the compound will occur. A further factor which must be considered is the fluctuation of temperature over the load cycle, since the mechanical stresses set up by this may be deleterious to the cable sheath and joints and, directly or indirectly, to the dielectric. This is of particular importance where unarmoured cables are laid in ducts. For this condition the permissible temperature is lower than for other methods of installation and is independent of operating voltage. The maximum permissible core temperature thus depends upon the nature of the dielectric, operating voltage, method of installation, and protective covering. Proposed values applying to this country are given in Table 1.

Table 1

Dielectric, finish, and mode of installation	Voltage	Type	Maximum permissible core temperature
Rubber-insulated, taped or braided or plain lead-covered, in buildings	Up to 1 000 V	Single or twin-core, concentric or multi-core	120° F. (49° C.)
Impregnated-paper-, jute-, or varnished-cambric-insulated, plain lead-covered or (where permissible) wire-armoured, in buildings	Up to 1 000 V	Single or twin-core, concentric or multi-core	160° F. (71° C.)
Impregnated-paper-insulated, lead-covered, with or without wire armour in air or laid direct in the ground or (wire-armoured only) drawn into ducts	Up to 10 kV	All types excluding 10-kV twin- and multi-core belted	(E.R.A.) 70° C.
	10 kV	Twin and multi-core belted	65° C.
	20 kV	All types excluding 20-kV multi-core belted	65° C.
	20 kV	Multi-core belted	55° C.
Impregnated-paper-insulated, plain lead-covered, drawn into ducts	All voltages	All types	50° C.

(ii) Ambient Temperature.

The ambient temperature at any situation in which cables are installed or are to be installed is defined as the temperature which would obtain in this situation under normal operating conditions, but excluding any increase of temperature in the immediate neighbourhood of the cables which may be due to the heat arising from them. Accepted values for this country which will not normally be exceeded are 90° F. (32·2° C.) applicable to cables installed in buildings, 25° C. for cables run in air, and 15° C. (soil temperature) for cables laid direct in the ground or drawn into ducts.

(iii) Core Temperature-Rise.

The maximum permissible core temperature-rise is the difference between the maximum permissible core temperature and the ambient temperature, and determines the current-carrying capacity of the cable.* Should the normal limit of ambient temperature be exceeded, the permissible core temperature-rise (and consequently the cable rating) will be reduced. If the normal temperature-rise θ is so reduced to θ' the cable rating is reduced by the factor $(\theta'/\theta)^n$, where n is $0 \cdot 5$ for cables in the ground or in ducts and $0 \cdot 54$ for cables in air. In general it is not safe to up-rate the cable for ambient temperatures lower than normal, as any increase in the core temperature-rise may contribute to deterioration of the cable, owing to cycles of thermal expansion, even though the limiting core temperature is not exceeded.

---

* See Bibliography, (6).

* Except in so far as this may be further limited by the permissible voltage-drop.

(d) Basic Formulae

Let $\theta°$ C. be the maximum permissible temperature-rise of the cable as determined from Section (*c*). Let R be the a.c. or d.c. resistance at the full temperature of each loaded core of the cable, in ohms/cm. The heat generated in the core flows through the internal thermal resistance of the insulation of the cable denoted by G' °C. per watt per cm. per loaded core. Additional heat may be generated in the sheath and armour by a.c. losses therein. The total heat generated then flows through the thermal resistance G_s of the serving, etc., and then either through the thermal resistance of the soil G_e, or partly through duct and soil, to the surface of the ground, which may with sufficient accuracy be taken as an isothermal at the ambient temperature. If the cable is run in air then a similar thermal resistance G_A may be determined as the inverse of the rate of thermal dissipation by convection, conduction, and radiation to the ambient atmosphere. The rating I of the cable in amperes is then

$$I = \left[\theta/R\left\{G' + n(G_s + G_e)(1 + \lambda)\right\}\right]^{\frac{1}{2}} \quad . \quad (1)$$

replacing G_e by G_A where appropriate. n is the number of loaded cores and λR represents the energy losses in sheath and armour in watts per amp.² per loaded core per cm.*

(e) Skin and Proximity Effects

With alternating current R may be represented by

$$R = R_0(1 + y + y_1) \quad . \quad . \quad . \quad . \quad (2)$$

where R_0 = d.c. resistance, y = skin-effect factor, and y_1 = proximity-effect factor. Although not strictly independent, y and y_1 are conveniently dealt with separately. The theoretical value of y for solid conductors has been shown by Arnold† to be applicable to stranded conductors of the type here envisaged. Thus,

$$1 + y = \frac{x(ber\,x\,bei'\,x - bei\,x\,ber'\,x)}{2\left\{(ber'\,x)^2 + (bei'\,x)^2\right\}} \quad . \quad (2.1)$$

where $x = \sqrt{(4\omega/R_0\,.10^9)}$. *Ber* and *bei* are the modified Bessel functions developed by Kelvin. The factor y has been tabulated for the required range. Arnold‡ has shown experimentally that for conductors at a moderate spacing such as occurs with systems of 2 or 3 single-conductor cables laid together, a very simple formula may be used for the proximity effect:—

$$y_1 = \alpha^2 y \text{ (single-phase)}; \; y_1 = 1 \cdot 5\alpha^2 y \text{ (three-phase)} \quad . \quad . \quad (2.2)$$

where $\alpha = 2r/s$, r = radius of conductor, and s = axial spacing between conductors.

These formulae are sufficiently accurate for cable-rating calculations even when applied to multi-conductor cables, but Arnold has also given more accurate formulae introducing the effect of resistance between strands on proximity effect, by means of a further parameter $x_1 = x\sqrt{p}$, where p depends upon the interstrand resistance. Thus for a solid conductor p is unity, while for cables with stranded conductors in practice p is $0 \cdot 8$ and an interstrand resistance greater than normal can be allowed for by a value of p less than $0 \cdot 8$. These formulae are referred to in the discussion and are quoted in the footnote* for convenience. For 4-core cables, when, as is usually presumed, the load is balanced and the fourth core idle, the same value of y_1 as for 3-core cables may be used. Some curves of y and y_1 for typical cables are shown in Fig. 1; the effect on current rating is not important for cables having a conductor cross-section less than $0 \cdot 2$ or $0 \cdot 3$ sq. in.

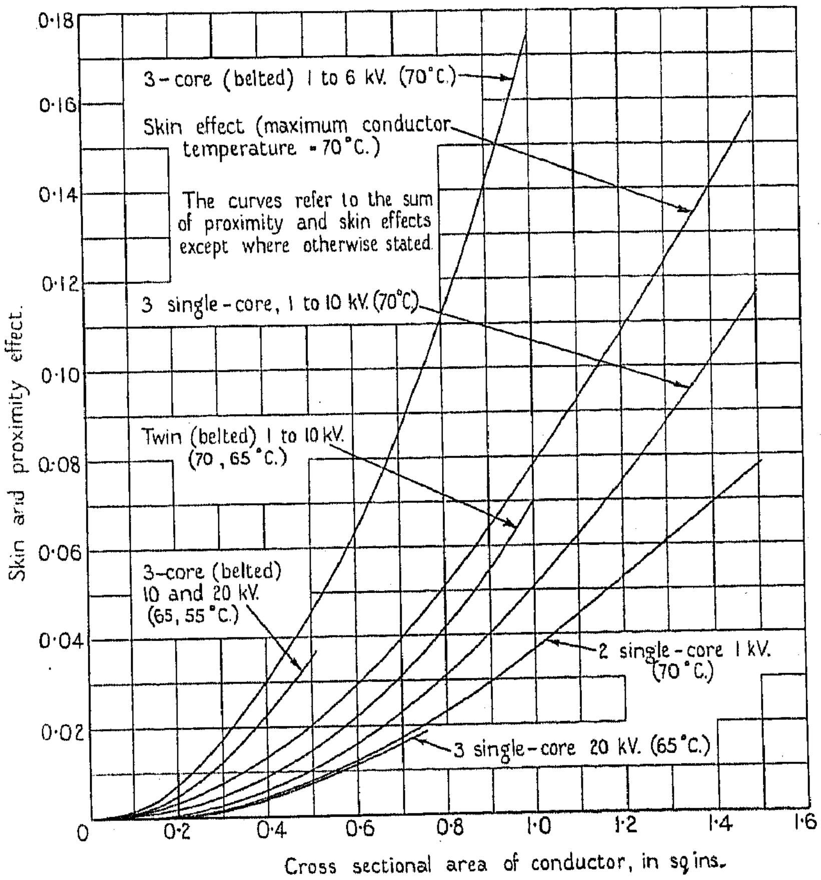


Fig. 1.—Skin and proximity effects.

(f) Sheath Losses

A number of papers on sheath losses in single-core cables have been published, so that it is only necessary to quote the formulae for the cases taken in rating tables, namely, two or three cables in a plane or three

---

* It is shown that the losses are usually proportional to I^2.

† See Bibliography, (7) and (8).

‡ *Loc. cit.*

* See Bibliography, (7), (8), and (9).

For two conductors carrying single-phase current:—

$$y_1 = \frac{\alpha^2 G(x_1)}{1 - \alpha^2 A(x_1) - \alpha^4 B(x_1)}$$

For three conductors carrying 3-phase current:—

$$y_1 = \frac{(3/2)\alpha^2\,G(x_1)}{1 - \frac{5}{24} \cdot \frac{F(x_1)}{G(x_1)}}$$

$$G(x) = \frac{x}{4} \cdot \frac{\text{ber}\,x\,\text{ber}'x + \text{bei}\,x\,\text{bei}'x}{\text{ber}^2 x + \text{bei}^2\,x} = \frac{xZ(x)}{4X(x)}$$

where $F(x)$ is the function giving the skin effect y, and $X(x)$ and $Z(x)$ are as defined by Russell (see "Alternating Currents," vol. i). The functions $F(x)$, $G(x)$, $A(x)$, and $B(x)$, have been tabulated by Arnold [see Bibliography, (8)].

cables in trefoil formation, the sheaths being bonded in all cases. The formulae are quoted from the paper by Wedmore, Morgan, and Whitehead,[*] but are essentially similar to those given by Arnold[†] and Carter.[‡]

2 cables in a plane:—

$$\lambda = \frac{R_s}{R} \cdot \frac{4\omega^2(\log 2\cdot 52s/d)^2 10^{-18}}{R_s^2 + 4\omega^2(\log 2\cdot 52s/d)^2 10^{-18}} + \frac{m\omega\,(d/2s)^2}{R(1+m^2)} \quad (3.1)$$

3 cables in a plane:—[§]

$$\lambda = \frac{R_s}{R} \cdot \frac{4\omega^2(\log 2\cdot 52s/d)^2 10^{-18}}{R_s^2 + 4\omega^2(\log 2\cdot 52s/d)^2 10^{-18}} + \frac{3m\omega(d/2s)^2}{R(1+m^2)} \quad (3.2)$$

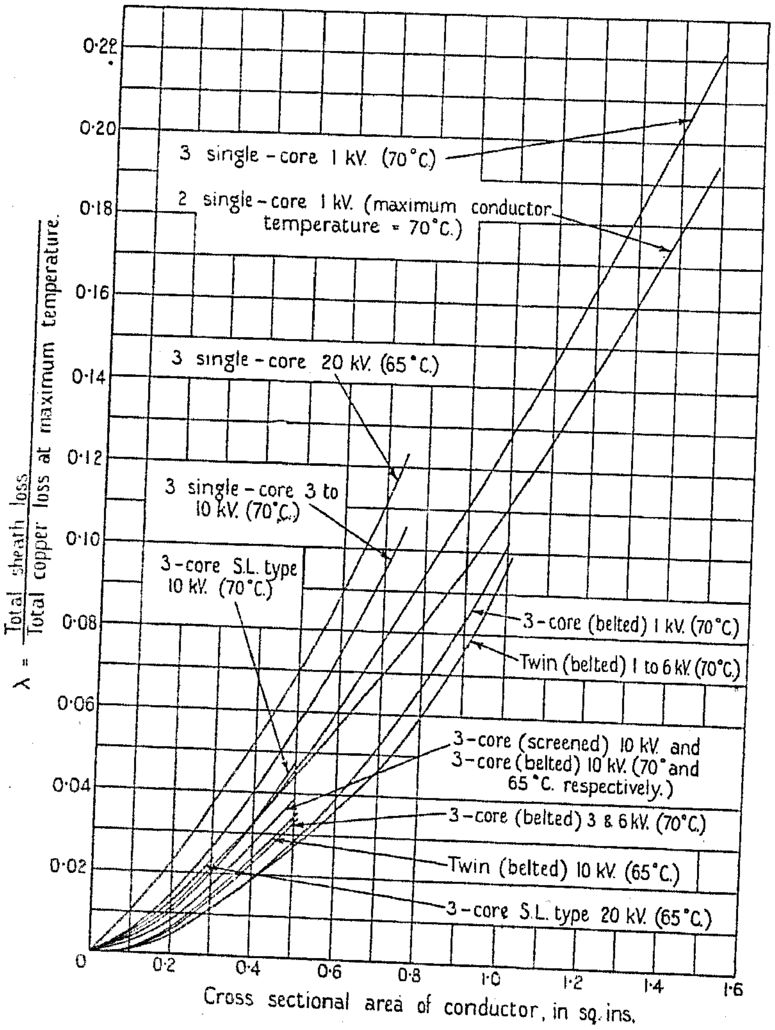


Fig. 2.—Sheath losses.

3 cables in trefoil:—

$$\lambda = \frac{R_s}{R} \cdot \frac{4\omega^2(\log 2s/d)^2 10^{-18}}{R_s^2 + 4\omega^2(\log 2s/d)^2 10^{-18}} + \frac{3m\omega(d/2s)^2}{R(1+m^2)} \quad . \quad (3.3)$$

s = axial spacing in cm; d = diameter of sheath in cm.; $\omega = 2\pi f$; R_s = resistance of sheath in ohm/cm.; $m = \omega/10^9 R_s$.

The last equation applies also to S.L. type cables. Fig. 2 shows some typical curves, the losses being only important for cables of conductor section greater than 0·2 sq. in.; three cables are supposed to be run in trefoil.

The following approximations to Carter's formulae[*] have been found satisfactory for the eddy losses in the sheaths of twin- and multi-core cables:

Twin cables:—

$$\lambda = \frac{4R_s}{R}\,\frac{m^2}{1+m^2}\left(\frac{2c}{d}\right)^2\left[\,1 + \frac{1}{4}\left(\frac{2c}{d}\right)^2\right] \quad . \quad (3.4)$$

Three-core cables:—

$$\lambda = \frac{16R_s}{5R}\,\frac{m^2}{1+m^2}\left(\frac{2c}{d}\right)^2 \quad . \; . \; . \; . \; . \; . \quad (3.5)$$

c = axial distance of conductor from centre of cable. The magnitude of the sheath losses in multi-core cables is not usually important for cables having a conductor section less than 0·3 sq. in. as in Fig. 2, while the effect on rating is small up to 0·5 sq. in.

Table 2

Size of cable, sq. in. ..	Up to 0·3	0·3 and 0·4	0·5	0·75	1·00	1·25 and 1·50
Ratio of rating with transposition to rating without	1·00	1·01	1·02	1·04	1·06	1·07

(g) Losses in Armouring

With armoured cables the factor λ of Section (*f*) must be increased by the addition of a similar factor λ_1, to take into account the energy losses in the armour. Owing to the heavy losses involved, single-core cables armoured with magnetic material should not be employed on alternating current. Non-magnetic armouring may be employed, and its effect may be represented largely by a decrease in the effective resistance of the sheath and a change in its dimensions. Details of such cases are given in Appendix 1 since they are outside the scope of the rating tables. It may be noted that, although up to a point addition of non-magnetic armour increases the losses, yet, when its resistance is sufficiently low, it has the effect of reducing the sheath losses, but this advantage is more than offset by the cost.

The loss in the armour of multi-core cables is due partly to eddy currents and partly to hysteresis, the former term being usually the more important. The theory of these effects is dealt with in Appendix 1 and leads to the formula:

$$\lambda_1 = \frac{16}{5}\,\frac{R_A}{R}\left(\frac{2c}{d_1}\right)^2 \frac{m_1^2}{1+m_1^2} + \frac{10^{-7}\delta\omega\eta}{Rd_1}\left[\frac{1\cdot 2\, c\mu}{d_1\{1 + (\mu\delta/d_1)\}}\right]^2 \quad . \quad (4)$$

d_1 = mean diameter of armour; δ = thickness of armour; R_A = resistance in ohm/cm.; $m_1 = \omega/10^9 R_A$; η = hysteresis loss in ergs per cm³ per gauss; μ = maximum permeability.

For single-wire armoured cables agreement with tests on cables and on the wires has been obtained on the assumption that η is 0·001 and that μ is 300, as mean values, although a considerable dispersion occurs in practice. Tests were made at the N.P.L. with 1-sq. in., 1-kV, 3-core wire-armoured cable before and after removal of the armouring. The difference in the losses so found was $0{\cdot}28_7$ at 200 amperes and $0{\cdot}28_9$ at 800 amperes, expressed as ratios to the ohmic conductor losses. Since the conductor temperature was greater

---

[*] See Bibliography, (10).
[†] *Ibid.*, (11).
[‡] *Ibid.*, (12).
[§] The formula in the text is for cables regularly transposed. With cables in air it may happen that in an untransposed run the cable having the highest sheath losses (No. 1 outer) is also exposed to the most severe thermal conditions, e.g. the upper cable of a group. Accordingly ratings are based on this condition. The formulae for the untransposed case are complicated and reference should be made to the original papers. Table 2 gives the magnitude of the effect.

[*] See Bibliography, (12).

(72° C.) in the second case than in the first (20° C.), the armour losses per (ampere)^2 would appear to increase with the current but only in the same ratio as the ohmic losses. The calculated value as in Table 3 was less than the measured but only by an amount which would be negligible as regards the rating.

For steel-tape armour the same formula should hold but the value of μ may be very great. Actually the hysteresis term does not change much with increase of μ when μ is large, since it tends to an asymptotic value. Accordingly a large value of μ, 5 000, was chosen and it was then found that the ratings of wire- and tape-armoured cables differed by less than 1 per cent up to 0·5 sq. in. and probably is less than 2 per cent for the largest sizes. The same ratings were therefore adopted both for single wire-armoured and steel-tape-armoured cables.

With S.L.-type cables account must be taken of the screening effect of the sheath currents which are in substantial opposition to the phase currents. The net current causing armour losses is, where i is the sheath current,

$$I\left(1+\frac{i}{I}\right)=I\left(1-\frac{j\omega M}{R_s+j\omega M}\right)=\frac{IR_s}{R_s+j\omega M} \quad (4.1)$$

The effective square current is thus $I^2R_s^2/(R_s^2+\omega^2M^2)$, which, since M is $2 \log (2s/d).10^{-9}$, is $I^2(1-\lambda)$. Thus the armour losses with S.L.-type cables must be multiplied by the reduction factor $(1-\lambda)$.

Table 3

THREE-CORE CIRCULAR-CONDUCTOR CABLES. CORE TEMPERATURE, 70° C. CALCULATED VALUES

Size, sq. in.	Voltage, kV	Wire-Armoured			Steel-Tape-Armoured		
		Eddy	Hysteresis	Total	Eddy	Hysteresis	Total
0·15	1	0·0059	0·007	0·0129	0·0048	0·0095	0·0143
0·50		0·039	0·035	0·074	0·031	0·051	0·082
1·00		0·202	0·077	0·279	0·196	0·143	0·339
0·04	10	0·0012	0·0019	0·0031	0·00095	0·0024	0·0034
0·15		0·0074	0·0087	0·0161	0·0060	0·012	0·018
0·50		0·044	0·040	0·084	0·052	0·041	0·093

The armour losses in multi-core cables of normal type are not of importance from the rating point of view for conductor sections less than 0·3 sq. in.

(h) Grouped Cables

Cables are frequently laid in groups. For ducts this is taken into account since the duct is considered as a whole, while for cables in air the thermal-dissipation constants include mutual heating effects. For groups of cables laid direct the current rating of any one of them is lower than that of the same cable when isolated, since the external thermal resistance is increased. A convenient way of expressing the effect is by group rating factors. Such factors have been calculated for a number of typical conditions of installation and the corresponding ratings set out elsewhere.* The group rating factor used is given by the expression

$$\sqrt{[1/(1-k+k_1k)]} \quad . \quad . \quad . \quad . \quad (5)$$

where $k=\theta_s/\theta_c$, and $k_1=G'_e/G_e$, the ratio of the external thermal resistance of the cable in question when it forms one of the group considered, to that when it is isolated, calculated from the formula given later. For rating purposes, however, the term k_1 is taken as unity for a complete system of cables. Thus for concentric and multi-core cables it applies to a single cable, but for single-core cables it applies to two cables carrying d.c. or single-phase a.c. load, or three cables carrying a balanced 3-phase load. Thus in determining k_1 for single-core cables, the external thermal resistance for the appropriate number and configuration of cables constituting the system must first be determined by the method set out in the paper, before calculating the group rating factor.

(2) INTERNAL THERMAL RESISTANCE OF CABLES

(a) Thermal Resistivity of Materials

(i) Dielectric.

The thermal resistivity of composite dielectrics such as those used in cable construction varies to some extent, but with improvement in manufacturing methods reliable values can be assigned representative of the upper limit for each class.

Tests carried out by the N.P.L. on typical low-voltage rubber-insulated single-core cables† gave values‡ ranging beween 630 and 720° C./watt/cm^3, with a mean value of 670° C./watt/cm^3. For the calculation of thermal resistance of rubber-insulated cables of all voltages the thermal-resistivity value has been taken as $K = 750$° C./watt/cm^3.

The same investigation§ gave values between 630 and 800° C./watt/cm^3 for impregnated-paper insulated low-voltage single-core cables, the mean value being 730° C./watt/cm^3. Owing to the more careful impregnation and tighter structure in high-voltage cables, the values assumed for the calculation of thermal resistance are $K = 750$° C./watt/cm^3 for cables operating at voltages up to and including 1 500 volts, and $K = 550°$ C./watt/cm^3 for higher voltages.

---

* See Bibliography, (13).

† *Ibid.*, (6).

‡ Including tape-braiding.

§ See Bibliography, (6).

Less experience has been obtained on varnished-cambric-insulated cables, and this class of dielectric is again difficult to render homogeneous, especially for multi-core cables. Tests on a wide range of cables have given results varying between 470 and 870° C./watt/cm^3 For the calculation of thermal resistance a value of $K = 750°$ C./watt/cm^3 has been assumed for cables of all types and voltages up to 20 kV.

(ii) Textile Protective Covering and Filling Material.

The thermal resistivity of the textile protective covering, excluding armouring,* may be taken as $K_1 = 500°$ C./watt/cm^3, the same value applying to the filling material for S.L.-type cables.

(iii) Screening Material.

Screened cables employ copper or aluminium tape. The standard values of thermal resistivity for these materials are $0\cdot26$ and $0\cdot5°$ C./watt/cm^3 respectively.

(b) Single-core and Concentric Cables

The internal thermal resistance of single-core and concentric cables is easily computed from rigid formulae set out below, in which the following notation is employed:

G' = thermal resistance from conductor to sheath or core to armour in S.L.-type cables.
G_s = thermal resistance of protective covering.
r = radius of conductor (inner conductor of a concentric cable).
r_1 = inner radius of second conductor of a concentric cable.
r_2 = outer radius of second conductor of a concentric cable.
r_3 = inner radius of outer conductor of a triple concentric cable.
r_4 = outer radius of outer conductor of a triple concentric cable.
r_5 = inner radius of lead sheath.
r_6 = outer radius of lead sheath.
τ = total thickness of textile protective covering over the sheath, i.e. thickness of bedding and thickness of serving, excluding thickness of armouring.
r_e = overall radius of complete cable, including bedding, armouring, serving, etc.

Single core—

$$G' = (K/2\pi) \log (r_5/r) \text{ °C./watt/cm.} \quad . \quad . \quad (6.1)$$

Concentric—

$$G' = (K/2\pi) \log (r_1 r_5^2/r r_2^2) \text{ °C./watt/cm.} \quad . \quad (6.2)$$

Triple concentric cables (balanced 3-phase loading)—

$$G' = (K/2\pi) \log \left(r_1 r_3^2 r_5^3/r r_2^2 r_4^3\right) \text{ °C./watt/cm.} \quad (6.3)$$

Triple concentric cables (d.c. 3-wire system)

$$G' = (K/2\pi) \log \left(r_1 r_3^2 r_5^2/r r_2^2 r_4^2\right) \text{ °C./watt/cm.} \quad (6.4)$$

For concentric cables the values obtained from the above formulae apply to the inner conductor, which is the hottest.

The additional thermal resistance of the protective covering (if any) is given by

$$G_s = \frac{K_1}{2\pi} \log \left(\frac{r_6 + r_e + \tau}{r_6 + r_e - \tau}\right) \text{ °C./watt/cm.} \quad . \quad (6.5)$$

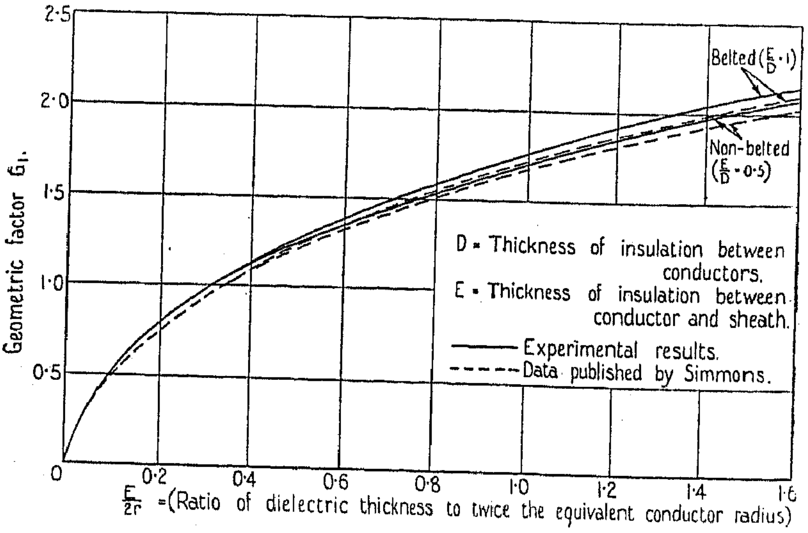


Fig. 3.—Geometric factors for twin-core circular conductor cables.

(c) Twin- and Multi-core cables

(i) Geometric Factor.

The computation of the internal thermal resistance of twin- and multi-core cables is more complicated. Rigid mathematical formulae cannot be determined, although mathematical expressions to fit the conditions have been derived by Mie and Russell. The general method of computation employs geometric factors in place of the logarithmic term in equations (6). Several methods of determining such factors have been devised, e.g. the measurement of the electrical resistance of models comprising electrodes immersed in an electrolyte, due to Konstantinowsky, and the measurement of electrostatic capacity between cylindrical electrodes and an outer cylinder which surrounds them, employed by a number

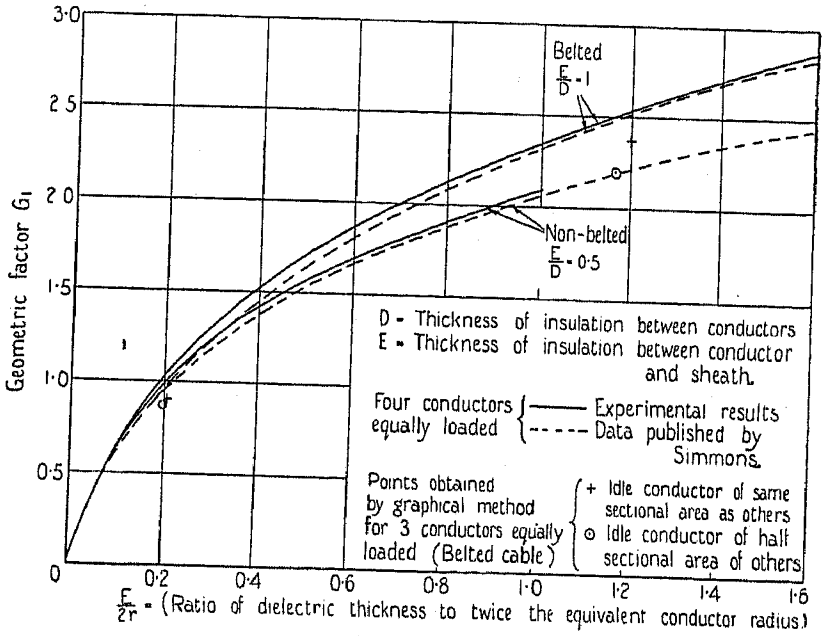


Fig. 4.—Geometric factors for four-core circular conductor cables.

---

* The value for armouring may be assumed as zero.

of investigators. Atkinson* carried out a comprehensive series of tests on models comprising copper-tube electrodes sweated on to tinfoil to represent the dielectric, using the electrical resistance analogy. A modification of this latter method was employed by the E.R.A. in a recent investigation. Electrodes representing the core and sheath were soldered to resistance-alloy sheet to represent the dielectric, and by measuring the electrical resistance of such models geometric factors were obtained for a wide variety of twin- and multi-core cables. Results were further checked by the graphical method devised by Wedmore,† and are shown in Figs. 3, 4, and 5, which also give values published by Simmons‡ based on his graphical solution.§

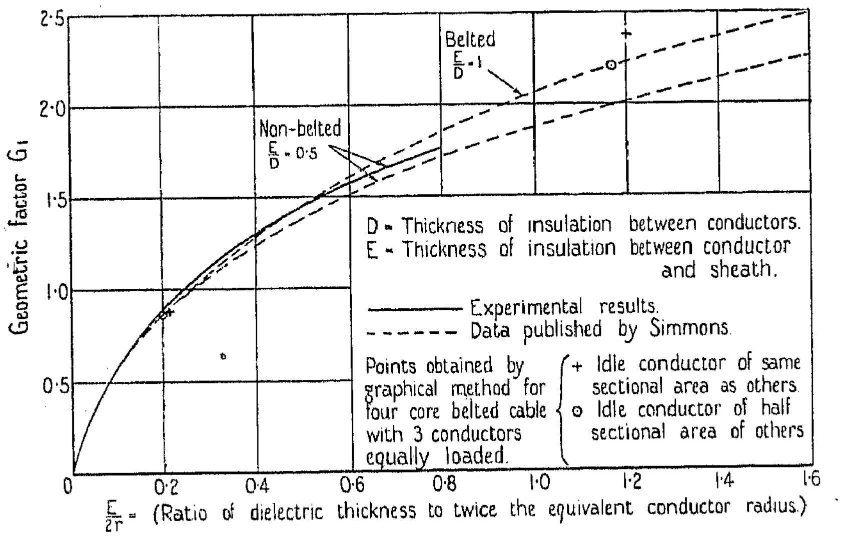


Fig. 5.—Geometric factors for three-core circular conductor cables.

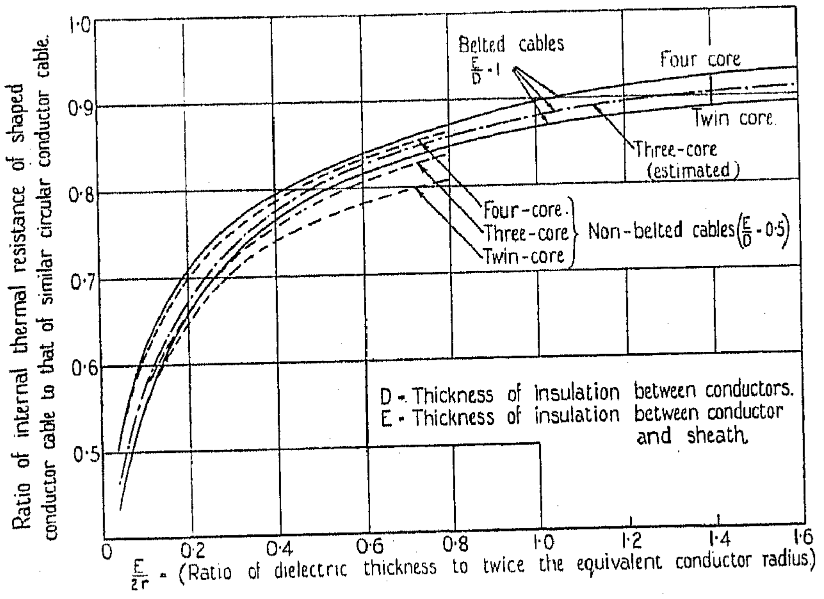


Fig. 6.—Sector correction factors for multi-core cables.

(ii) Shaped Conductors.

The use of shaped conductors reduces the thermal resistance of a cable, the precise effect depending upon the configuration of the conductor. Some tests on this aspect were carried out by Atkinson, and sector correction factors were published by him.|| These were based, however, on results obtained from three-core models only. The investigation by the E.R.A. was more comprehensive, covering twin-, three-, and four-core models having a wide range of dimensions and constructed in accordance with modern conductor shapes. The results are shown in Fig. 6.

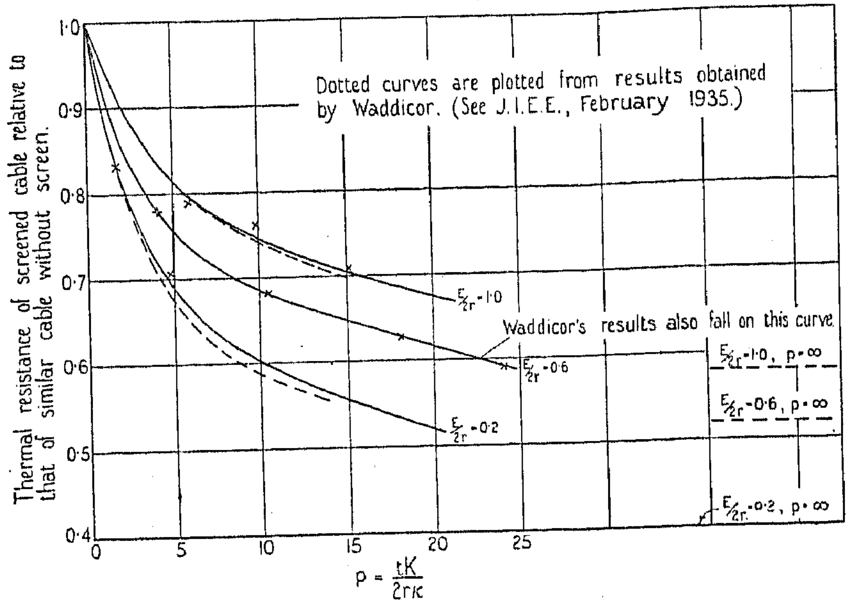


Fig. 7.—Effect of screening on thermal resistance of three-core circular-conductor cables with zero belt thickness.

(iii) Screened Cables.

Screening reduces the thermal resistance of a cable by providing additional heat paths along material of high thermal conductivity, in parallel with the path through the dielectric. For circular-conductor cables, the electrolytic method has been employed by Konstantinowsky and Tchiassny to study this effect, while an interesting method employing resistance networks to represent the cable sections has been described by Waddicor.* Investigations carried out by the E.R.A. employed models constructed as previously described, provided with an additional copper strip sweated to the resistance alloy and surrounding the core electrode to simulate the screen. This screen was so dimensioned as to have the correct relative conductance, as deter-

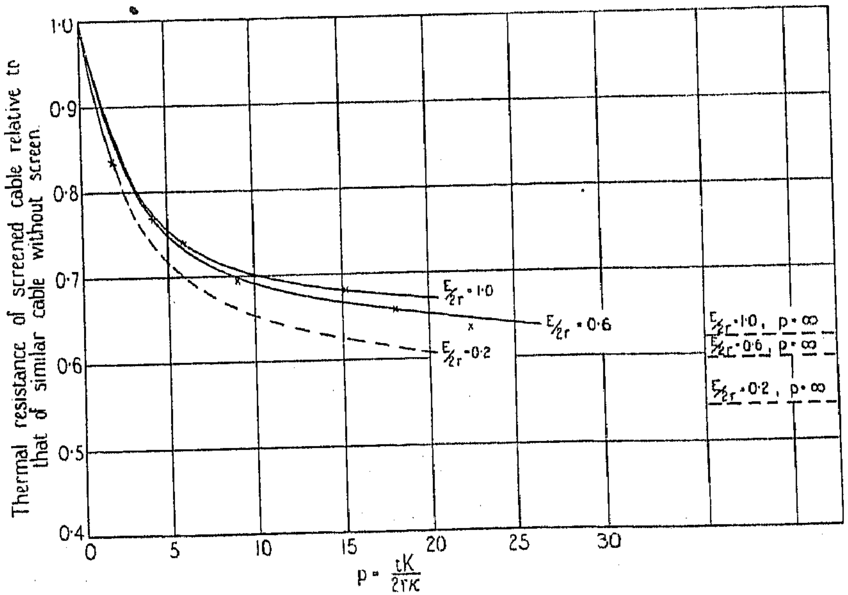


Fig. 8.—Effect of screening on thermal resistance of three-core shaped-conductor cables with zero belt thickness.

---

* See Bibliography, (14).
† *Ibid.*, (1).
‡ *Ibid.*, (15).
§ *Ibid.*, (16).
|| *Ibid.*, (14).

* See Bibliography, (17).

mined by the parameter $tK/(2r\kappa)$, where t is the thickness of the screen, r the radius or equivalent radius of conductor, K the thermal resistivity of the dielectric, and κ the thermal resistivity of the screen material. By this means the effect was studied for both circular and shaped conductor cables, the results in the former case agreeing well with Waddicor's. Figs. 7 and 8 give the screening factors so obtained, while Fig. 9 presents them in a different form compared with those of Konstantinowsky and Tchiassny for circular conductors. The discrepancy between the latter and those obtained by the E.R.A. may be ascribed to the unreliability of the electrolytic method.

It can be seen that the reduction in thermal resistance due to screening is less affected by operating voltage in the case of shaped conductor cables than in cables with circular conductors.

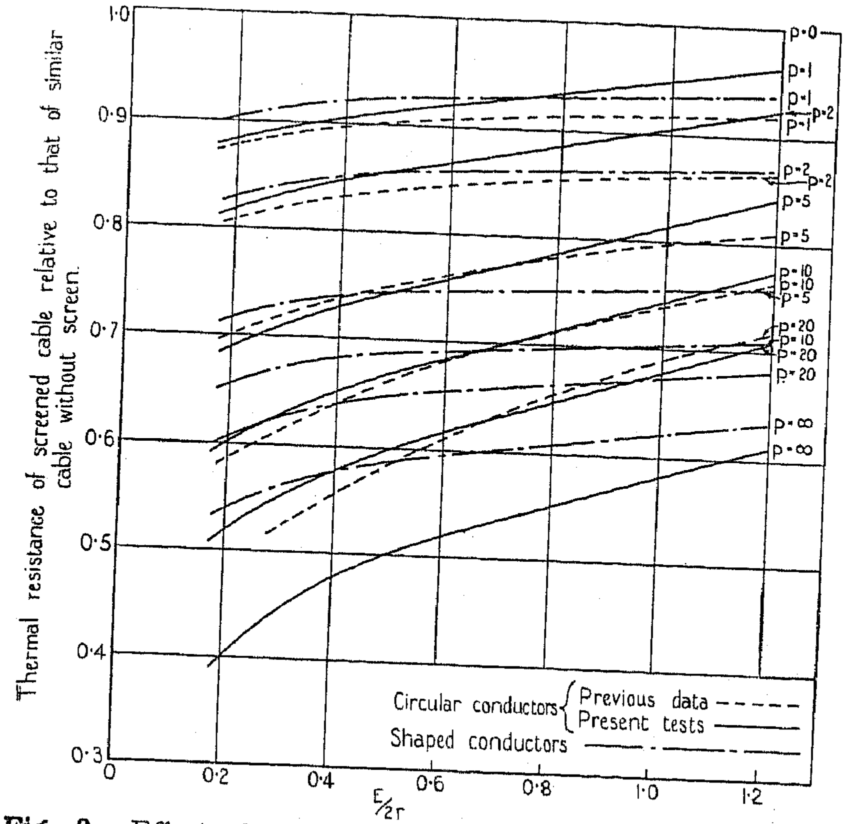


Fig. 9.—Effect of screening on thermal resistance of three-core cables with zero belt thickness.

(iv) S.L.-Type Cables.

In S.L.-type cables the lead sheath round each core may be assumed isothermal. Waddicor* has treated the subject semi-graphically and concludes that in some cases the thermal characteristics of such cables may be somewhat inferior to those of screened cables. The graphical method of Wedmore has been used to obtain the curves shown in Fig. 10, giving the relationship between G_f, the thermal resistance of the filling material between sheaths and armouring, and F, the minimum thickness of this part of the heat path, in terms of the thermal resistance of the filler material.

The thermal resistance of S.L.-type cables is then given by

$$G' = K/2\pi \log \left\{(r + E)/r\right\} + G_f \text{ °C./watt/cm.} \quad (6.6)$$

where E is the thickness of dielectric between conductor and lead sheath.

(v) Protective Covering.

For all twin- and multi-core cables except S.L.-type cables, the thermal resistance of the protective covering (if any) is given by the expression previously adduced for concentric cables.

For S.L.-type cables, however, since G' includes the thermal resistance to the armouring, that of the protective covering is given by

$$G_s = K_1/2\pi \log (r_e/r_a) \text{ °C./watt/cm.} \quad . \quad (6.7)$$

where r_a is the radius over the armouring.

(3) CABLES LAID DIRECT IN THE GROUND

(a) Thermal Resistivity of Soils

(i) Method of Measurement.

It has long been known that thermal resistivity values obtained by the box method, in which a sample of soil removed from the site is investigated in the laboratory, cannot be directly applied to buried cables, and for this reason the application of a correction factor of $\frac{2}{3}$ to such results has been generally used to allow for the compacting of the soil on site. Such a procedure is, however, empirical, and while it may under certain circumstances satisfy the requirements, this is not necessarily the case. Methods of determining the thermal resistivity of soils on site have therefore been devised, such methods involving the measurement of the temperature gradient around a heater buried in the ground.

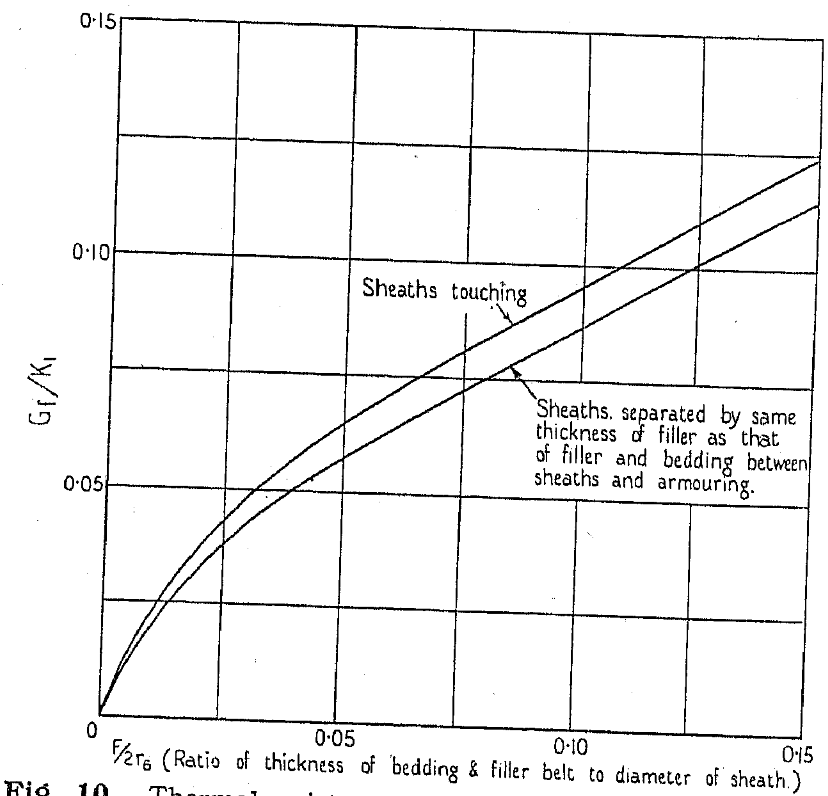


Fig. 10.—Thermal resistance of filler in three-core S.L. type cables.

The E.R.A. has been carrying out investigations of this nature for a number of years, and as a result has issued recommendations regarding the methods to be employed.* The apparatus may be installed in a hole of the appropriate diameter bored to the required depth, or alternatively a trench may be excavated and the apparatus placed in a cavity cut in the wall. Precautions must be taken to ensure intimate contact between the soil and the heater shell, and to fill in the borehole or trench to reproduce as nearly as possible the original soil conditions.

---

* See Bibliography, (17).

* See Bibliography, (18).

In one form, developed by the N.P.L., the apparatus consists of a copper sphere of 9 in. diameter containing a heater wound on a spherical former, the whole being supported on a tube of low thermal conductance which serves to bring the leads to the surface. Thermo-junctions sweated to the heater shell, and others located at known distances from the axis, determine the temperature gradient in the surrounding soil, the thermal resistivity of which is calculated from the expression

$$g = 4\pi(T_1 - T_2)/[W(1/r_1 - 1/r_2)]\ \text{°C/watt/cm}^3 \qquad (7)$$

where T_1 and T_2 are the temperatures (°C.) measured at distances r_1 and r_2 cm. respectively from the centre of the sphere, and W is the energy dissipated by the heater, in watts.

Table 4

THERMAL RESISTIVITY OF SOILS

Type of Soil	Form of Apparatus	Depth	Date	Load	Shell Temp.	Base Temp.	Thermal Resistivity in °C./watt/cm³ between points distant from axis		
							Shell to 6 in.	6 in. to 24 in.	Shell to base
				watts	°C.	°C.			
Sand	9-in. sphere	4 ft. 8 in.	Sept. 1934	26	46·7	13·9	386	132	184
			May 1936	25	24·6	7·5	165	83	103
	3-in. sphere	5 ft.	Sept. 1935	11	69·2	15·0	—	—	229
			May 1936	11	33·0	7·5	—	—	109
Clay*	9-in sphere	6 ft.	May 1934	91	39·8	7·4	82	46	52·3
	3-in. sphere	6 ft.	May 1934	51	70·1	9·6	—	—	56·9
	3-in. cylinder	6 ft.	April 1935	132	64·8	7·6	—	—	55·5
	2-in. cylinder	6 ft.	Oct. 1936	10	6·3 deg. rise		—	—	52·8
Loam over sand and gravel† ..	9-in. sphere	3 ft.	May 1931	—	—	—	See note‡	65	—
			Dec. 1931	—	—	—		85	—

* Tests carried out by Mr. E. Fawssett at Newcastle.

† Tests carried out by Dr. E. Griffiths at the N.P.L.

‡ The shell temperature was higher (by an amount which varied with the season) than would be expected from those measured by the external thermo-junctions.

In alternative forms the heater is contained in a 3-in. sphere or a cylindrical copper shell as developed by E. Fawssett, having an axial length not less than four times its diameter, the construction being in other respects similar to the above.

For practical purposes, the external soil temperature is measured at the mean depth of the heater and at one point only sufficiently remote for the temperature to be undisturbed. The thermal resistivity is then given by:—

$$g = a\theta/W\ \text{°C/watt/cm}^3 \quad . \quad . \quad . \quad (7.1)$$

where θ is the temperature-rise in deg. C. of the heater shell above the base, W is the energy dissipated by the heater in watts, and a is a constant for the apparatus concerned.

The constant for a spherical heater, assuming spherical heat flow, is $4\pi r$, where r is the external radius of the sphere in cm. For cylindrical heaters the constant must be determined by calibration of the apparatus against a sphere in the same medium. This form of apparatus has the advantage that it is more easily installed, and, if of small dimensions, can be operated from a car-type battery where no other supply is available.

It should be observed that equation (7.1) will give the average thermal resistivity of the soil from heater shell to base. Should any linear variation occur due to drying out of the soil near the heater this will not be apparent unless intermediate thermo-junctions are installed. This has been done in the investigations carried out by the E.R.A. on certain soils, but the former value corresponds to practical conditions of cable installation. Typical results are shown in Table 4.

The investigations have covered a number of different soils, and have shown that the subject is a complex one, the precise effect of some of the factors involved having still to be determined. From the tests already made, however, certain general facts have emerged which are of considerable importance in connection with buried cables.

(ii) Type of Soil.

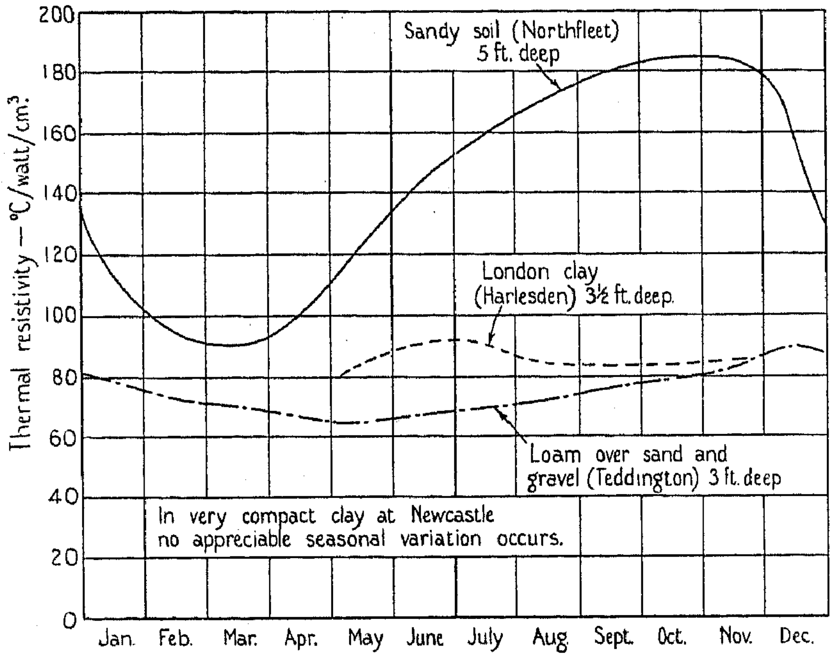
Thermal resistivity varies over a wide range with type of soil. Speaking generally, soils which will hold a relatively high percentage of moisture have a low thermal resistivity, while porous soils have a high thermal resistivity. Examples of these two types are clay and sand respectively, while light loamy soils will fall between these extremes. Much will depend, however, on the drainage facilities, so that a gravel or chalk, although itself porous, may have as low a thermal resistivity as clay if the soil strata below it tend to prevent the water from draining away from it, or if it is low-lying and subject to waterlogging through proximity to rivers or the sea.

(iii) Seasonal Variations.

For certain soils the thermal resistivity varies with the season. In the case of clay the variation observed has been unimportant, but with sandy loam values have been found to vary between 65 and 90 over a period of a year, while in sand the variation was very marked, the minimum and maximum values at a depth of 5 ft. being 90 and 180 respectively, repeating over a period of two years' observation.

In general, the low values occurred in the spring and the high values in the autumn.

Such variations are probably due to changes in the moisture content and temperature of the soil, but it has not been possible to correlate these factors. It appears, however, that high thermal-resistivity values occur at periods when the moisture content is low and the ground temperature high, and vice versa, but the limiting values of the former do not necessarily coincide with those of the latter. Furthermore, in sand, variation in moisture content at a depth of 3 ft. appears to have less effect on the thermal resistivity at that depth than a relatively smaller variation at a depth of 5 ft. The tests in sand at 3 ft. indeed showed no clear seasonal variation, the values fluctuating more rapidly but over a much narrower range. This effect is probably due to changes in atmospheric conditions which would not penetrate to greater depths.



At Northfleet and Harlesden, temperature differences were measured from sphere surface to base.

At Teddington, temperature differences were measured between two thermocouples buried in the ground 1½" & 20" respectively from the surface of the sphere.

All tests carried out with 9" spheres.

Fig. 11.—Seasonal variation in thermal resistivity of certain soils.

Typical curves showing the seasonal variations observed in different soils during the course of the investigations are given in Fig. 11.

On the assumption that the thermal resistivity of the soil is uniform, general mean factors may be applied to the standard ratings to allow for a particular known resistivity different from 120. The factor is 1·05, 0·93, 0·85, for resistivities of 100, 150, and 200, respectively.

(iv) Effect of Depth.

The evidence on the effect of depth on thermal resistivity is not conclusive. Comparative tests at different depths were carried out in a very compact clay and in sand. In the former case there is some slight indication that the thermal resistivity as measured with a 9-in. sphere at a depth of 6 ft. is higher than at 10 ft., although the difference did not exceed 5 per cent. With a 3-in. sphere, however, the difference observed was of the order of 20 per cent. It is possible, however, that this effect may have been wholly or partially due to differences in the watt density at the sphere surface, as discussed in the next Section. In sand, correcting for seasonal variation, no difference was observed when using a 9-in. sphere at a depth of 10 ft. and 5 ft., but at 3 ft. very much lower values were obtained.

(v) Effect of Thermal Dissipation.

There is some evidence to indicate that the thermal-resistivity values obtained depend upon the watt density at the surface of the sphere. Typical curves are shown in Fig. 12 for clay, in which no appreciable seasonal variation was observed. In sand the results, when corrected for seasonal variation, indicated that thermal dissipation had no effect. It is considered advisable, however, to carry out the tests at such a loading that the temperature-rise of the heater shell shall be of the same order as that of the buried cable.

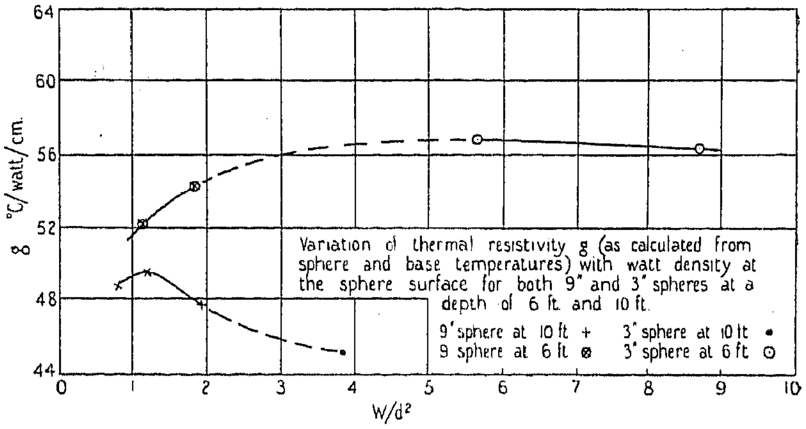


Fig. 12.—Tests in clay soil (Newcastle). Variation of thermal resistivity *g* (as calculated from sphere and base temperatures) with watt density at the sphere surface for both 9-in. and 3-in. spheres at a depth of 6 ft. and 10 ft.

(d = diameter of sphere.)

(b) External Thermal Resistance of Cable

(i) Standard Formula.

It is generally assumed that the surface of the ground above a buried cable is an isothermal, since it is in contact with free air. The isothermals in the soil therefore form a system of coaxial circles, and the thermal resistance from the outer covering of an isolated cable (single-core, concentric, or multi-core) to the earth's surface is given by

$$G_e = \frac{g}{2\pi}\log\frac{\sqrt{l^2-r_e^2}+(l-r_e)}{\sqrt{l^2-r_e^2}-(l-r_e)}\ \text{°C./watt/cm.} \qquad (8)$$

$$= (g/2\pi)\log\left\{(2l-r_e)/r_e\right\}\ \text{approx.}$$

where g = thermal resistivity of the soil in °C./watt/cm³
l = depth of cable axis below ground surface in cm.
r_e = outside radius of cable in cm.

(ii) Effect of Depth.

From equation (8) it might be thought that the external thermal resistance of a cable becomes greater as the depth at which it is laid is increased. This is only the case, however, if the thermal resistivity of the soil remains constant at different depths.

In the case of cables laid near the surface, earlier experiments* showed that the external thermal resistance became greater as the depth increased up to 4 ft. 6 in. in made ground naturally compacted under its own weight over only a few years. Subsequent tests† on actual cables buried at greater depths in very closely compacted clay at Newcastle gave values of 45 and 49° C./watt/cm. for the total thermal resistance of the earth path at 10 ft. and 20 ft. respectively, and by substituting these values in the standard formula given in the previous section the thermal resistivity of the soil is found to be 48·3° C./watt/cm³ at 10 ft. depth and 47·0° C./watt/cm³ at 20 ft. It would appear, therefore, that the assumption of constant thermal resistivity at depths of this order is valid at least for such a soil. Table 5 gives depth rating factors which have been compiled on this assumption and which take into account both the variation of external thermal resistance and the internal thermal resistance of the cable.

Table 5

DEPTH RATING FACTORS

Depth of laying	Cables for voltages up to and including 1·5 kV			Cables for voltages above 1·5 kV
	Up to 0·04 sq. in.	0·04 to 0·5 sq. in.	Above 0·5 sq. in.	All sizes
ft.				
6	0·92	0·89	0·87	0·94
9	0·91	0·88	0·86	0·92
12	0·89	0·86	0·84	0·90
15	0·87	0·84	0·82	0·89
18	0·85	0·82	0·80	0·87

(iii) Effect of Grouping.

When a number of cables are laid in close proximity to one another, the external thermal resistance of any one of the group is given by‡

$$G_e = \frac{g}{4\pi}\sum_1^n \log\frac{(l_1+l_n-r_e)^2+y_n^2}{(l_1-l_n-r_e)^2+y_n^2}\ \text{°C./watt/cm.} \quad . \quad (8.1)$$

where
g = thermal resistivity of the soil in °C./watt/cm³,
l_1 = axial depth of the cable considered in cm.,
l_n = axial depth of each other cable of the group in cm., and
r_e = outside radius of the cable considered in cm.,

and

y_n = horizontal axial distance between the cable considered and each other cable in the group in cm.

This formula can be applied to any number of cables laid in any configuration. For the simple case of two similar cables laid horizontally and touching, the external resistance of either of them becomes

$$G_e = \frac{g}{2\pi}\log\frac{(2l - r_e)^2}{r_e^2\sqrt{5}}\ \text{°C./watt/cm. (approx.)} \quad (8.2)$$

For three similar cables in trefoil formation and touching with vertex downwards, the external thermal resistance of the lowest and hottest becomes

$$G_e = \frac{g}{2\pi}\left[\log\left(\frac{2l_1 - r_e}{r_e}\right) + \log\left\{\frac{(l_1 + l - r_e)^2 + r_e^2}{(l_1 - l - r_e)^2 + r_e^2}\right\}\right]\ \text{°C./watt/cm.} \quad . \quad (8.3)$$

where l_1 = axial depth of the lowest cable,
and l = axial depth of the upper cables.

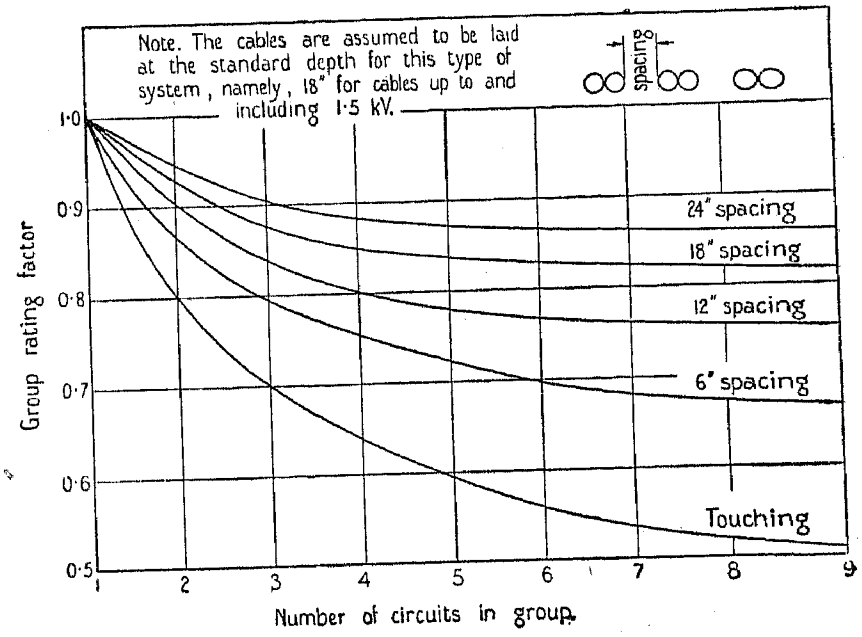


Fig. 13.—Group rating factors for two single-core cables laid side by side and touching.

The quantity G_e from equation (8.1) permits the determination of k_1 and thence of the group rating factor given in equation (5), Section (1) (h), provided k, the ratio of sheath to core temperature-rise, is known. It has been found possible to use average values of k for different classes of cables with sufficient accuracy, namely 0·75 for two single-core cables, 0·875 for three single-core cables, 0·625 for concentric, 0·62 for triple concentric, 0·675 for twin, 0·7 for 3-core belted or screened, 0·66 for S.L. type, 0·64 for 4-core. Group rating factors so determined are given in Figs. 13, 14, 15, and 16.*

(c) End Effects

In the case of a cable of finite length laid direct in the ground, longitudinal conduction will occur in the core and sheath, and also in the surrounding soil. This effect may, in certain conditions, result in alleviation of the temperature-rise of the cable as computed on the assumption of infinite length. As demonstrated in Appendix 2, however, such alleviation will only be appreciable for a length of run of the order of less than 10 ft.

---

* See Bibliography, (1). † *Ibid.*, (19). ‡ *Ibid.*, (20)

* See also Bibliography, (30).

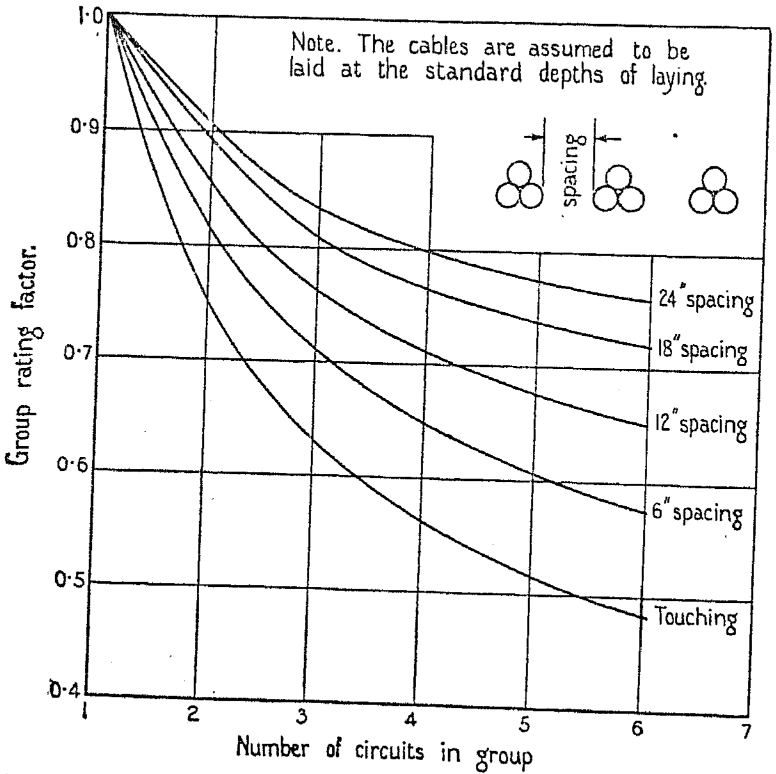


Fig. 14.—Group rating factors for three single-core cables in trefoil formation.

(d) Intermittent Ratings

Standard ratings have in this country been based on the maximum load which can be carried continuously, although directions for transient loading have previously been given,* together with a number of heating and cooling curves. In the U.S.A. ratings are based on a 50 per cent, 75 per cent, and 100 per cent daily load factor, that is, the ratio of the actual ampere-hours to the maximum ampere-hours. However, the continuous rating of a cable may be regarded as a physical property and should therefore be tabulated as the characteristic quantity, while variable loads may be classified and an allowance estimated for the various classes.

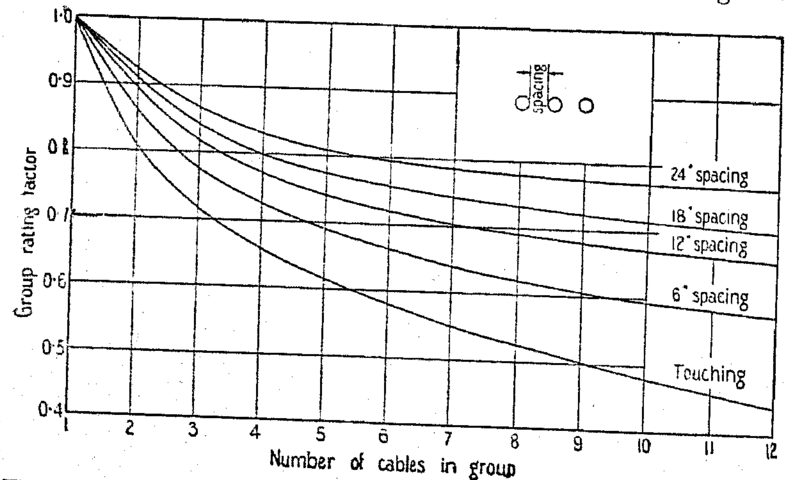


Fig. 15.—Group rating factors for concentric, twin, and multi-core cables in horizontal formation.

It is shown in Appendix 3 that if t is the time elapsed since switching on the load, θ_c the maximum core temperature-rise for continuous loading, k is as given in Section (b), then the actual core temperature-rise $\theta_c(t)$ is given by

$$\theta_c(t)/\theta_c = \alpha^2\{(1 - e^{-t/SG'})(1 - k) + k\beta\} \quad . \quad (9.1)$$

where αI is the load, I the continuous rating of the cable, S the thermal capacity of the cable, namely the sum of the thermal capacity of the loaded conductors and one-half the thermal capacity of the insulation and sheath all divided by the number of loaded conductors, and G' the internal thermal resistance. The quantity β is given by

$$\beta = \frac{-Ei(-2x) + Ei(-l^2/Dt) + e^{-2x}\log 2}{\log(16l^2/d^2)} \quad . \quad (9.2)$$

where $x = d^2/(16Dt)$, d = overall diameter of cable, D = thermal diffusivity of the soil in watt-cm. units, l = depth of cable, and Ei is the exponential integral function tabulated in Jahnke and Emde's Tables of Functions, and elsewhere.

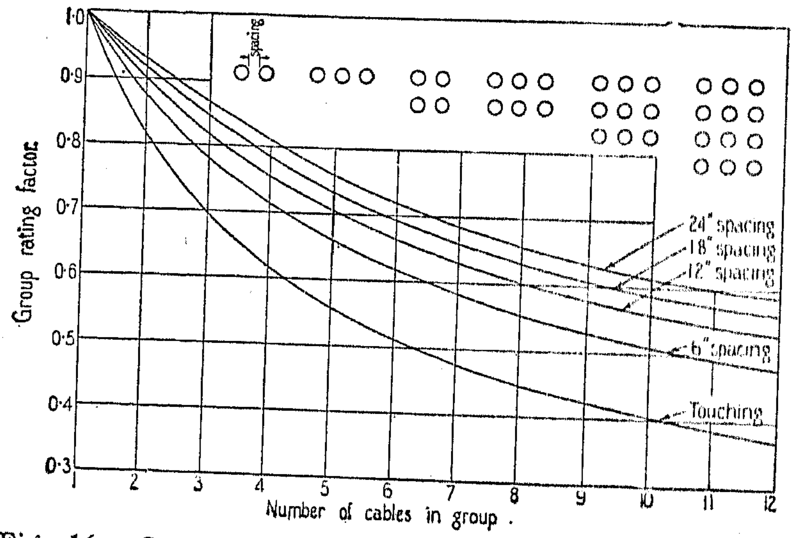


Fig. 16.—Group rating factors for concentric, twin, and multi-core cables in tier formation.

One frequent type of variable load occurs when a peak-hour load is superimposed upon a substantially continuous load. Let the continuous load be $\alpha_0 I$, giving a temperature-rise $\alpha_0^2\theta_c$, then $\theta(t)$, the increase of temperature due to the peak load, must not exceed $(1 - \alpha_0^2)\theta_c$, whence

$$\text{maximum peak-hour load} = I\sqrt{(\alpha^2 + \alpha_0^2)}$$

$$= I\left[\alpha_0^2 + \frac{1 - \alpha_0^2}{(1 - e^{-t/SG'})(1 - k) + k\beta}\right]^{\frac{1}{2}} \quad . \quad (9.3)$$

For standardization purposes t is taken as 1 hour and α_0 as either 0·5 or 0·75. Fig. 17 shows the variation with different conditions. It may be observed that cables can be discriminated according to diameter over lead and that voltage may then be neglected while multi-and single-core cables do not differ greatly. The main uncertainty lies in the diffusivity of the soil, which varies with nature of soil and also seasonally. Moisture increases the specific heat and decreases the thermal resistivity, and therefore its effect tends to be compensated as regards the diffusivity. The type of soil having a thermal resistivity of 120 would probably have a diffusivity rather less than 0·01. But in view of the doubt attending such correlations it has been decided to adopt a value for D of 0·02 to permit a margin of safety, and also to take the 1-kV curves for multi-core cables as generally applicable. This is also desirable since it is not easy or convenient to allow for the localized thermal resistance which may occur at the boundary between cable and soil when a heavy load is carried for a short time. The values are rather greater than those previously obtained* for a 20-kV cable which was tested in this way, due partly to differences in construction and installation.

---

* See Bibliography, (1) and (2).

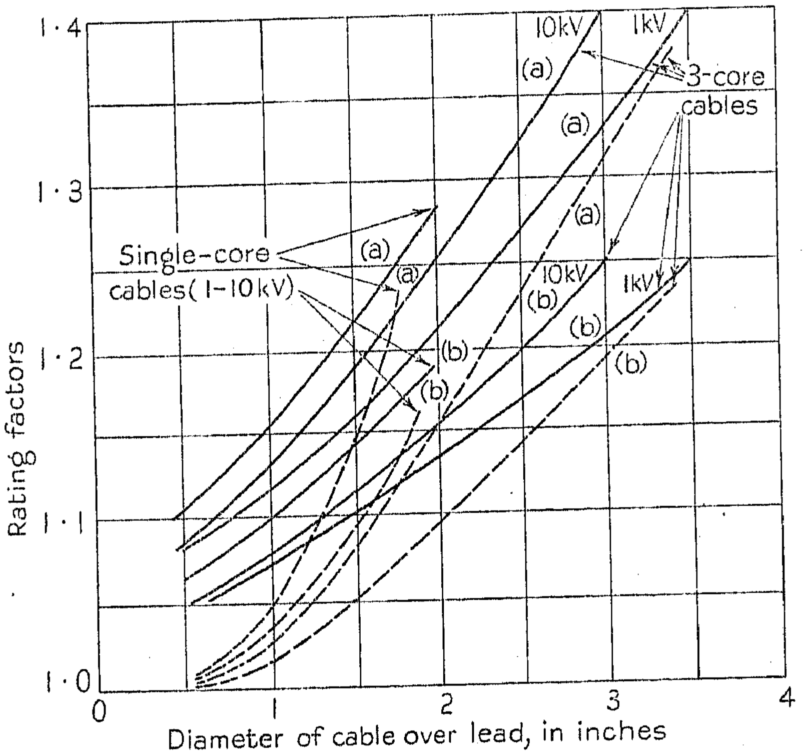


Fig. 17.—Rating factors for peak-hour loading.

— Cables laid direct.
-- Cables in air (1–10 kV).
(*a*) 50 % continuous loading.
(*b*) 75 % continuous loading.

Apart from peak-hours, loads are usually less at night and, in industrial areas, may be very small at the weekend. This gives rise to a cyclic loading having a period T during which it is supposed, for simplicity, that the load is applied for a time t_0. The effect may be simulated by applying a positive source of heat initially, an equal negative source at t_0, a positive source added again at T, and so forth. The temperature-rise θ after $n + 1$ cycles at the same load would therefore be less than θ_c, the maximum temperature-rise for continuous loading, and is

$$\theta = \sum_{\nu=0}^{\nu=n} \theta(\nu T + t_0) - \theta(\nu T) \quad . \quad . \quad (9.4)$$

This series rapidly converges and may be replaced for a large number of cycles by

$$\frac{\theta}{\theta_c} = \sum_{\nu=0}^{\nu=n} \frac{\theta(\nu T + t_0) - \theta(\nu t)}{\theta_c} + \frac{t_0}{T}\left(1 - \frac{\theta(nT + t_0)}{\theta_c}\right) \quad (9.41)$$

n need only be taken as 3 or 4 if a large number of cycles occur, but in industrial areas having a 6-day load, n is taken as 6 and the second term is neglected. The rating for this type of cyclic loading is the square root of the relative temperature alleviation, namely

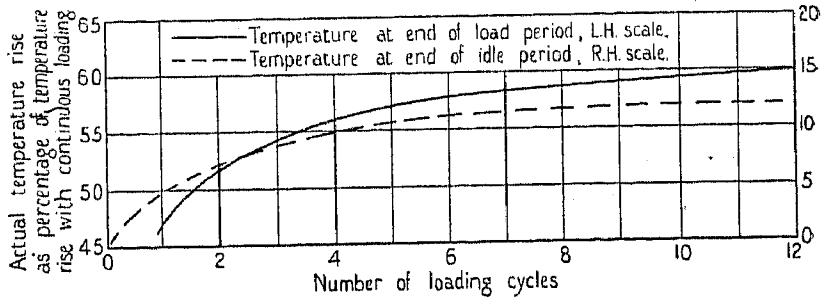


Fig. 18.—Relationship between temperature-rise with continuous and intermittent loading.

$$I(\text{cyclic})/I(\text{continuous}) = \sqrt{(\theta_c/\theta)} \quad . \quad (9.5)$$

To evaluate this, $\theta(t)/\theta_c$ requires to be known as a function of t. This can be found from an experimental heating or cooling curve in an actual instance, but can be found theoretically from equations (9.1) and (9.2). Since the cycle is normally 24 hours and t_0 is several hours, (9.1) and (9.2) reduce to (α being now unity)

$$\left.\begin{aligned} &\theta(t)/\theta_c = 1 - k + k\beta \quad \text{and} \quad \theta(0) = 0 \\ &\beta = \{-0\cdot577 - \log x + Ei(-l^2/Dt)\}/\log\,(16l^2/d^2) \end{aligned}\right\}(9.6)$$

since t is now large so that x and $e^{-t/SG'}$ are small, x being $d^2/(16Dt)$.

After some consideration of conditions in various

Table 6

Method	Calculation from formulae									Heating curves [see Bibliography, (1)].			
Diffusivity (watt-cm. units)	0·005				0·02					0·2 sq. in. 3-core 66 kV	0·15 sq. in. 3-core 11 kV	0·15 sq. in. 3-core 20 kV	0·35 sq. in. 3-core 20 kV
Diam. of cable (cm.)	2	10	2	10	2	10	2	10	6	6·1	8·2	6·3	8
Depth of laying (cm.)	46		92		46		92		61	61	61	61	61
$\theta_s/_0\theta_s$ in percentage	74	60	68	50	86	79	77	67	76	79	87	82	82

---

* See Bibliography, (1).

areas, it was decided to adopt a cycle in which the cable is loaded for 8 hours and idle for 16 hours each day, and that this cycle would be repeated at least 5 or 6 times. Fig. 18 shows the variation of sheath temperature in such conditions at the end and beginning of consecutive cycles for a cable of 10 cm. diameter laid at 46 cm. or 18 in. in soil of diffusivity 0·005. Comparatively little further change occurs after 5 or 6 cycles, so that the rating corresponding to a large number of cycles may be adopted. Equation (9.6) may then be replaced by

$$\frac{\theta}{\theta_c} = 1 - k + k\left[\frac{-Ei(-x_0) + 0\cdot 53 + 0\cdot 33\left\{Ei(-0\cdot 1x_0) - Ei(-l^2/10Dt_0)\right\}}{\log\,(16l^2/d^2)} + \frac{1}{3}\right] \quad . \quad . \quad . \quad (9.7)$$

The last term represents θ'/θ_s and $x_0 = d^2/(16Dt_0)$, where $t_0 = 8$ hours and $\theta' =$ sheath temperature-rise at time t.

Table 6 shows typical results of calculation from the foregoing, and determination from heating curves by means of (9.4).

The diffusivity of the soil in the heating tests mentioned is not known with certainty, but was high, probably lying between 0·01 and 0·03. Again, the difference between calculation and experiment would not exceed about 2 per cent on the actual rating. More detailed tests made by Fawssett on cables at Newcastle, where the properties of the soil were better known, gave agreement with calculations within certain limits. For example, while agreement could be obtained over the first 24 hours or for 10 days, excluding the first day, the constants in the two cases were not quite the same. Analysis of the results, however, showed the possibility of a change of diffusivity with time which could arise both by secular changes in the soil due to temperature gradient and also, if the soil were not absolutely homogeneous, to the change in temperature distribution with time. For the present application it is only necessary that the formula should hold either for a period of an hour or so or else for periods from 8 hours onwards, and this seems to be the case.

It has finally been decided, as before, to adopt a diffusivity of 0·02 for rating purposes, and it is then found that different types and sizes of cable vary little in the increase permitted for cyclic loading as is shown by Table 7.

(4) CABLES IN DUCTS

(a) Theory

In the following treatment of the subject it is assumed that the length of duct line over which conditions are uniform is great in comparison with the depth at which it is laid, as is generally the case. Where this is not so, a correction must be applied for longitudinal conduction. This aspect is dealt with in Appendix 2, where it is demonstrated that no correction is necessary where the length of line exceeds ten times the depth of laying.

The thermal resistance from the conductor of any cable laid in a single-way duct to the surface of the ground can be divided into four parts in series, namely: G' from the surface of the conductor to the outer surface of the cable, G_A from the outer surface of the cable to the inner wall of the duct, G_d from the inner to the outer wall of the duct, G_p from the outer wall of the duct to the surface of the ground.

The first has been fully dealt with in Section (2) of this paper.

The second depends upon the three components of the total heat emitted from the surface of the cable, namely radiation, convection, and conduction.

The radiation loss is given by the formula:

$$H_r = \pi d\sigma(T_0^4 - T_1^4)E_1E_2/(E_1 + E_2 - E_1E_2) \text{ watts/cm.} \quad (10.1)$$

where

d = overall diameter of the cable in cm.
σ = Stefan's constant = $5\cdot 71 \times 10^{-12}$.
T_0 = absolute temperature of the cable surface.
T_1 = absolute temperature of the inner surface of the duct.
E_1 and E_2 = emissivities of the cable and duct surfaces respectively.

The emissivities of various kinds of cable and duct surface are given in Table 8. Eccentricity of the cable

Table 7

RATING FACTORS FOR CYCLIC LOADING OF TYPICAL CABLES

(8 *hours on and* 16 *hours off*)

Size, sq. in.	1 kV conc. triple core or twin	10 kV conc. and twin	3-core 1 kV	Belted 20 kV	3-core screened 20 kV	3-core S.L. type 20 kV	Two single-core cables laid flat and touching (up to and including 1·5 kV)	Three single-core cables in trefoil formation		
								1 kV	6 kV	20 kV
0·04	1·05	1·10	1·07	1·10	1·12	1·11	1·06	1·06	1·11	1·11
0·15	1·06	1·11	1·08	1·12	1·14	1·13	1·07	1·07	1·13	1·12
0·3	1·07	1·13	1·08	1·14	1·16	1·14	1·08	1·08	1·14	1·13
0·5	1·08	1·14	1·08				1·08	1·08	1·15	1·14
1	1·09		1·11				1·09	1·09		
1·5							1·09	1·09		

in the duct has probably a negligible effect on the radiation loss.

The convection loss is given by the formula

$$H_c = k_c d^{3/4} \theta^{5/4} \text{ watts/cm.} \quad . \quad . \quad (10.2)$$

where

k_c = constant depending on the ratio of cable diameter to duct diameter, as shown in Fig. 19, and

θ = temperature-difference between the cable and the inner wall of the duct in deg. C.

Table 8

Thermal Emissivities of Duct and Cable-Sheath Materials. Temperature Range 30° to 50° C. [From N.P.L.]

Description of specimen	Emissivity
Pure lead surface, as supplied	0·20
Ditto, burnished	0·14
Ditto, after 6 days' exposure	0·18
Ditto, after 11 days' exposure	0·18
Ditto, after 40 days' exposure	0·21
Ditto, after 57 days' exposure	0·23
A new pure lead surface with a coating of tallow, 1–3 mm. in thickness	1·0
Oxidized pure lead surface with 0·5 mm. coating of tallow	1·0
Chemical lead surface, heavily pitted . .	0·62
Lead (tarnished sample)	0·56
Lead (sample from cable after tests in Harlesden duct)	0·57
Lead and petroleum jelly	0·35
Lead and graphite grease	0·94
Lead and colloidal grease	0·93
Lead and belmoline grease	0·80
Antimonial lead surface (new)	0·20
Ternary alloy surface (new)	0·28
B.N.F. ternary alloy, No. 2	0·39
Ternary alloy	0·14
Ternary alloy and petroleum	0·34
Ternary alloy and flake graphite grease . .	0·98
Ternary alloy and colloidal grease	0·99
Ternary alloy and belmoline grease	0·82
Bright wire armouring	0·31
Bituminous compound covering	1·0
Glazed earthenware surface representative of the internal surfaces of the ducts used in the investigation (moulded tiles 8 in. square) . .	0·96
Ditto, cut from a large slab	1·0
Fibre surface (3-in. diameter tube)	0·93
Concrete surface, either black (slightly glazed), white or grey	1·0

The above expression is only true when the cable is concentric with the duct. For a cable lying on the bottom surface of the duct the convection loss is reduced by approximately 30 per cent for a ratio of cable diameter to duct diameter of 0·5.

The conduction loss is given by the formula

$$H_d = 2\pi K_a \theta / \omega \text{ watts/cm.}^* \quad . \quad . \quad (10.3)$$

where

K_a = thermal conductivity of the medium—in this case air, viz. $25 \cdot 2 \times 10^{-5}$ watts per cm³ per deg. C.

$\omega = \cosh^{-1}\{(r_e^2 + r_d^2 - c^2)/2r_e r_d\}$

r_e = overall radius of cable in cm.

r_d = internal radius of duct in cm.

c = distance between axis of cable and axis of duct in cm.

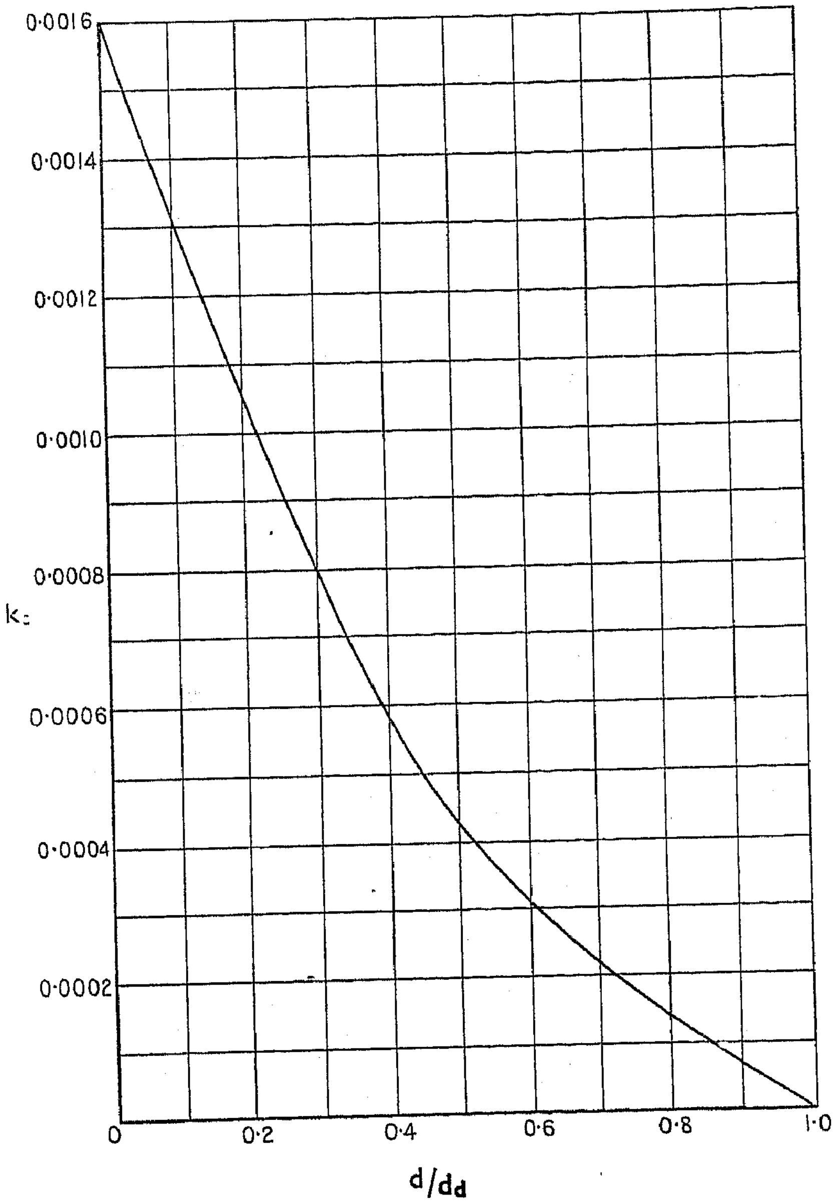


Fig. 19.—Relation between convection constant k_c and ratio of cable diameter d to duct diameter d_d.

If x is the minimum clearance between cable and duct wall in cm., i.e. $x = r_d - r_e - c$, and if x is small compared with r_d and r_e, the expression for conduction loss may be simplified to

$$H_d = 2\pi K_a \theta \sqrt{\frac{r_e r_d}{2x(r_d - r_e)}} \text{ watts/cm.} \quad . \quad (10.31)$$

The total heat emitted from the cable surface is then the sum of the above three components, namely:

$$H = H_r + H_c + H_d \text{ watts/cm.} \quad . \quad (10.4)$$

---

[*] By analogy with the capacitance between two cylinders one within the other —see Russell's "Alternating Currents," vol. 1, p. 165.

and the overall thermal resistance between cable surface and inner surface of duct is given by:

$$G_A = \theta/H \text{ °C./watt/cm.} \quad . \quad . \quad . \quad (10.5)$$

The thermal resistance from the inner to the outer wall of the duct is given by

$$G_d = \frac{g_d}{2\pi} \log \frac{r_0}{r_d} \text{ °C./watt/cm.} \quad . \quad . \quad (11)$$

where

g_d = thermal resistivity of the duct material in °C./watt/cm³

r_0 = outside radius of the duct in cm.

r_d = inside radius of the duct in cm.

Finally, the thermal resistance from the outer surface of the duct to the ground surface is given by

$$G_p = \frac{g}{2\pi} \log \frac{\sqrt{l^2 - r_0^2} + (l - r_0)}{\sqrt{l^2 - r_0^2} - (l - r_0)} \text{ °C./watt/cm.} \quad (12)$$

where

g = thermal resistivity of the soil in °C./watt/cm³

l = depth of the duct axis below the surface of the ground in cm.

r_0 = outside radius of the duct in cm.

If l is large compared with r_0, this latter expression simplifies to

$$G_p = \frac{g}{2\pi} \log \frac{2l - r_0}{r_0} \text{ °C./watt/cm.} \quad . \quad (12.1)$$

In the case of multi-way ducts it is convenient to consider the thermal resistance between each loaded cable and the surface of the ground separately. This may be divided into the same four parts in series as in the case of a single-way duct. Of these the first two (G' and G_A) are calculated as before. The thermal resistance from the inner surface of each duct-way to the surface of the ground, however, will vary as between individual cables, and will depend not only upon the position of the cable considered in the duct cluster, but also upon the loading of the others.

The thermal resistance from the inner wall of any duct-way to the outer surface of the duct cluster is not amenable to rigid mathematical treatment, owing to the perforations in the duct structure which distort the normal lines of heat flow. An added complication is due to the fact that the outer surface is not an isothermal, since in practice a duct cluster is not circular in section. It is, therefore, necessary to define the duct section as an equivalent circle of radius R_e whose area is equal to that enclosed by the outer walls of the duct cluster. If the latter approximates to a square whose length of side is a, then

$$R_e = 0{\cdot}564a \quad . \quad . \quad . \quad . \quad (12.2)$$

A convenient method of determining the thermal resistance of this part of the heat path is to construct the heat-flow diagram* for the particular case under consideration. Such a diagram may be constructed for any case in which the isothermals become circles concentric with the axis of the duct system at or near the equivalent radius defined above, and the method is thus confined to symmetrically loaded duct systems. It is further necessary to preclude longitudinal convection through the duct-ways, or, alternatively, to apply a correction for this, and to assume that, as the resistance to the flow of heat through the air in unoccupied duct-ways or pilot holes is much higher than that through the duct material, all the heat will flow through the latter. This assumption may be false if any of the duct-ways contain idle cables, but again a correction can be applied as indicated later in Section 4(*c*) of the paper.

For the case in which one cable only, that situated in the centre duct-way of a nine-way cluster, is loaded, the method is illustrated in Fig. 20. An arbitrary number of "tubes" of heat are drawn emanating from the centre duct-way, the surface of which is assumed to be isothermal. These are produced to a point outside the duct cluster at which the isothermals (which intersect them in such a way as to form an orthogonal system) become circles concentric with the axis of the duct system. The radius at which this occurs may be denoted by R_s. Then the thermal resistance from the inner wall of the centre duct-way to a radius R_s, assuming a uniform medium, is given by the product of the temperature-drop between these limits (measured in arbitrary units by the number of isothermals) and the thermal resistivity of the duct material, divided by the number of "tubes" of heat emanating from the centre duct-way. It should be noted that the latter value is eight times the number shown in the diagram, since only one-eighth of the section through the duct is shown. The thermal resistance from the inner wall of the centre duct-way to the outer surface of the duct cluster (defined by the equivalent radius R_e) is obtained by deducting from the above resistance that of a layer of duct material between radii R_e and R_s, which is given by $(g_d/2\pi) \log (R_s/R_e)$, where g_d is the thermal resistivity of the duct material.

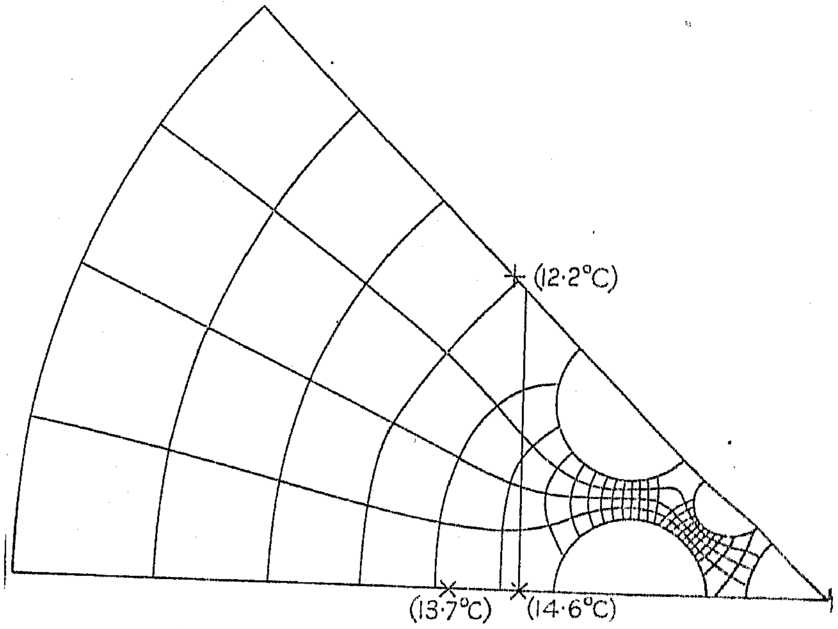


Fig. 20.—Heat-flow diagram for a 9-way duct system with only middle cable loaded.

Values in brackets are observed temperature-rises for a dissipation of 0·367 watt/cm. in middle cable.

When several cables in the duct cluster are loaded, the method can still be applied provided that, as previously mentioned, the loading is symmetrical. A typical diagram is shown in Fig. 21. The method of construction is similar to that already described, but it should be noted that the number of " tubes " of heat emitted from each duct-way must be proportional to the watts dissipated from the cable in that duct-way. In the case illustrated equal loading was assumed. When the system is symmetrical about a central duct-way containing a loaded cable, the inner wall of this duct-way may be assumed isothermal as in the previous case, but in other cases the heat-flow is not necessarily normal to the walls of the duct-ways.

---

* See Bibliography, (1).

In computing the resistance to heat-flow from any one of several loaded cables in a duct cluster from the diagrams, the method is in principle the same as that employed in the case in which the middle cable only was loaded, the temperature-drop from the inner wall of the duct-way to a radius R_s and the number of " tubes " of heat emitted from the cable under consideration being used. Where the wall of the duct-way is not isothermal, its mean temperature above that at a radius R_s must be estimated. In deducing the resistance between radii R_e and R_s the expression becomes $(g_d/2\pi\nu) \log (R_s/R_e)$, where ν is the ratio of the heat emitted from the cable under consideration to that emitted from all the loaded cables.

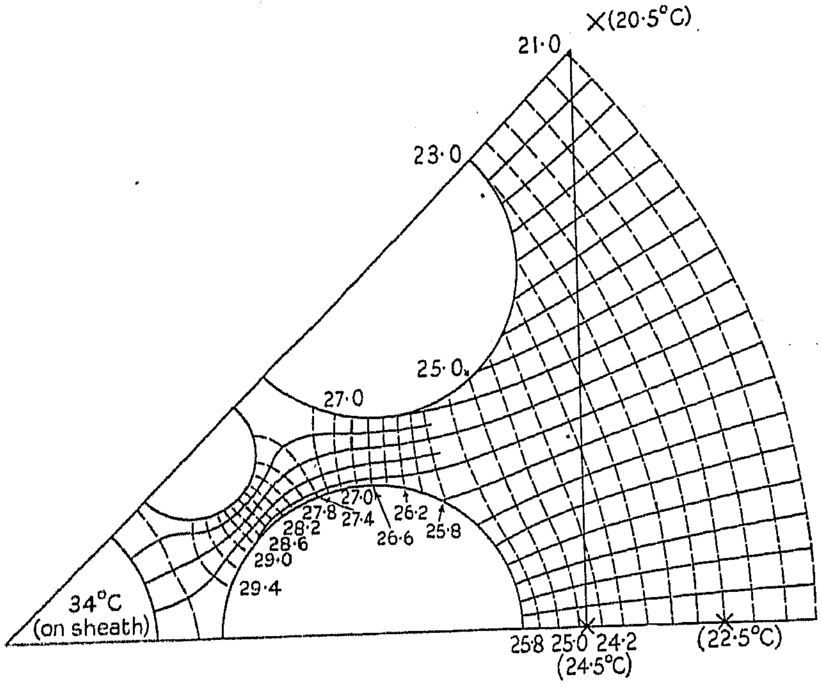


Fig. 21.—Heat-flow diagram for a 9-way duct system having all cables equally loaded.

Values shown are temperature-rises above undisturbed ground temperature at same depth, for a dissipation of 0·078 watt/cm. in each cable. Temperatures in brackets are observed values for this loading.

The radius R_s for any given duct cluster is found to depend upon the number and location of the loaded cables, and may considerably exceed R_e. The error introduced by assuming an isothermal surface at the latter radius is, however, small, since if any serious distortion occurs it will indicate that the thermal resistance inside the radius R_e has increased greatly, and an error in the value of the thermal resistance beyond this radius is of relatively less importance.

The expression given previously for the thermal resistance from the outer surface of a single-way duct to the surface of the ground must be modified for multi-way duct clusters, for which the resistance of this part of the heat path to heat flow from any one cable is given by G_p/ν, where G_p has the value given above for a single-way duct. For n equally loaded cables, ν is $1/n$.

Although it is preferable to construct the heat-flow diagram for the particular case considered, yet for convenience a list is given here of values for some common conditions for ducts having a ratio of internal duct diameter to duct spacing of 0·824, a ratio of pilot hole diameter (in the case of a nine-way duct) to internal duct diameter of 0·43, and a minimum thickness of duct material (between adjacent duct-ways or between inner wall of an outer duct-way and outer surface of duct cluster) of 0·214 × internal duct diameter. The thermal resistance from the inner wall of the duct-way specified to the outer surface or equivalent, in terms of the thermal resistivity (g_d) of the duct material is as follows:

(i) One cable in a single-way duct .. $0 \cdot 057 g_d$
(ii) Centre cable in a nine-way duct:
  (1) Centre cable only loaded .. $0 \cdot 70 g_d$
    (assuming no heat-flow across other duct-ways).
  (2) Centre cable only loaded .. $0 \cdot 31 g_d$
    (assuming some heat-flow across other duct-ways*)
  (3) All cables equally loaded .. $1 \cdot 04 g_d$
(iii) Any cable in a four-way duct:
  All cables equally loaded .. .. $0 \cdot 13 g_d$

It is interesting to compare the above value for the centre cable in a nine-way duct when that cable only is loaded and no heat-flow assumed across the other duct-ways, with the value determined from tests described elsewhere† on the electrical resistance of a sheet-metal model of a similar duct. The latter gave the thermal resistance as $0 \cdot 86 g_d$, but the ratio of duct diameter to duct spacing was slightly greater. On correcting for this on the assumption that, approximately, the resistance is inversely proportional to the minimum thickness of the duct material, a value of $0 \cdot 715 g_d$ was obtained.

(b) Experimental Work

A previous investigation‡ supplied information on the current rating of cables drawn into a six-way duct, both for the case of one loaded cable and for that in which all six cables were loaded, but apart from this very little experimental work had been done.

In order to verify results obtained by the theoretical methods set out in the previous section, a series of full-scale tests were therefore carried out by the E.R.A. at Harlesden on a nine-way earthenware duct-system laid with a cover of approximately 3 ft. in London clay. The total length of duct was 36 ft. The duct-sections were provided with pilot holes, and the diameter of the duct-ways was $3\frac{1}{2}$ in. Plain lead-sheathed, 600-volt, concentric cables were drawn into each duct-way.

Seven conditions of loading were investigated as follows:

(i) All nine cables equally loaded.
(ii) All nine cables with graded loading.§

---

* See Section (4)(c) and Fig. 28.

† See Bibliography, (21).

‡ *Ibid.*, (1).

§ That is, with their individual currents so adjusted as to give the same temperature-rise on all loaded cables.

Table 9

CURRENT LOADING AND MID-SHEATH TEMPERATURE-RISE FOR TESTS WITH ALL NINE CABLES LOADED

Position of cable		L.H. outer	Middle	R.H. outer
(*a*) *Equal Loading.*				
	Current	←	225 amp.	→
Top row	Temperature-rise above undisturbed ground temperature	29 deg. C.	31 deg. C.	29 deg. C.
Middle row		33 deg. C.	34 deg. C.	33 deg. C.
Bottow row		25 deg. C.	28 deg. C.	28 deg. C.
(*b*) *Graded Loading.*				
Top row	Current	240 amp.	212 amp.	245 amp.
	Temperature-rise	38·6 deg. C.	40·3 deg. C.	39·3 deg. C.
Middle row	Current	212 amp.	187 amp.	220 amp.
	Temperature-rise	39·5 deg. C.	39·5 deg. C.	39·9 deg. C.
Bottom row	Current	280 amp.	246 amp.	260 amp.
	Temperature-rise	36·4 deg. C.	38·8 deg. C.	38·8 deg. C.

(iii) Middle cable idle, remainder equally loaded.
(iv) Middle cable idle, remainder with graded loading.
(v) Three outer cables around the bottom corner equally loaded.
(vi) Middle cable only loaded.
(vii) One bottom corner cable only loaded.

In all cases the idle cables (if any) remained in the duct-ways.

Table 10

MID-SHEATH TEMPERATURE-RISE, MIDDLE CABLE IDLE, GRADED LOADING ON REMAINING EIGHT CABLES, AT APRIL 2ND, 1935

Position of cable		Left-hand outer	Middle	Right-hand outer
Top row ..	Current, amperes	255	240	256
	Temperature-rise, deg. C...	29·5	29·8	30
Middle row ..	Current, amperes	191	Nil	209
	Temperature-rise, deg. C...	30·5	27	29·5
Bottom row ..	Current, amperes	278	270	278
	Temperature-rise, deg. C...	23	29·5	29

The temperature of the cable sheaths and of the surface of the duct cluster were measured by means of thermocouples, and a thorough survey of the ground temperatures was made by similar couples and resistance thermometers carefully buried at predetermined positions around the duct system.

Some results of the tests are given in Tables 9 to 11, and Figs. 22 to 27.

The current rating deduced from the tests described is based on the sheath temperature-rise at the mid-point of the duct system measured on the hottest cable in the case of equal loading, or on all cables in the case of graded loading, where the rating is taken as the average current of the loaded cables.

The values applying to the various conditions of loading investigated are shown in Table 12, and correspond to a conductor temperature-rise (above undisturbed ground temperature at the same depth) of 35 deg. C. They are calculated from the measured sheath temperatures, using the known internal thermal resistance of the cable, and on the assumption that the temperature-rise of any cable is proportional to the square of the current which it carries. The error due to this assumption will be small, since the tests were all carried out at currents giving approximately the same temperature-rise.

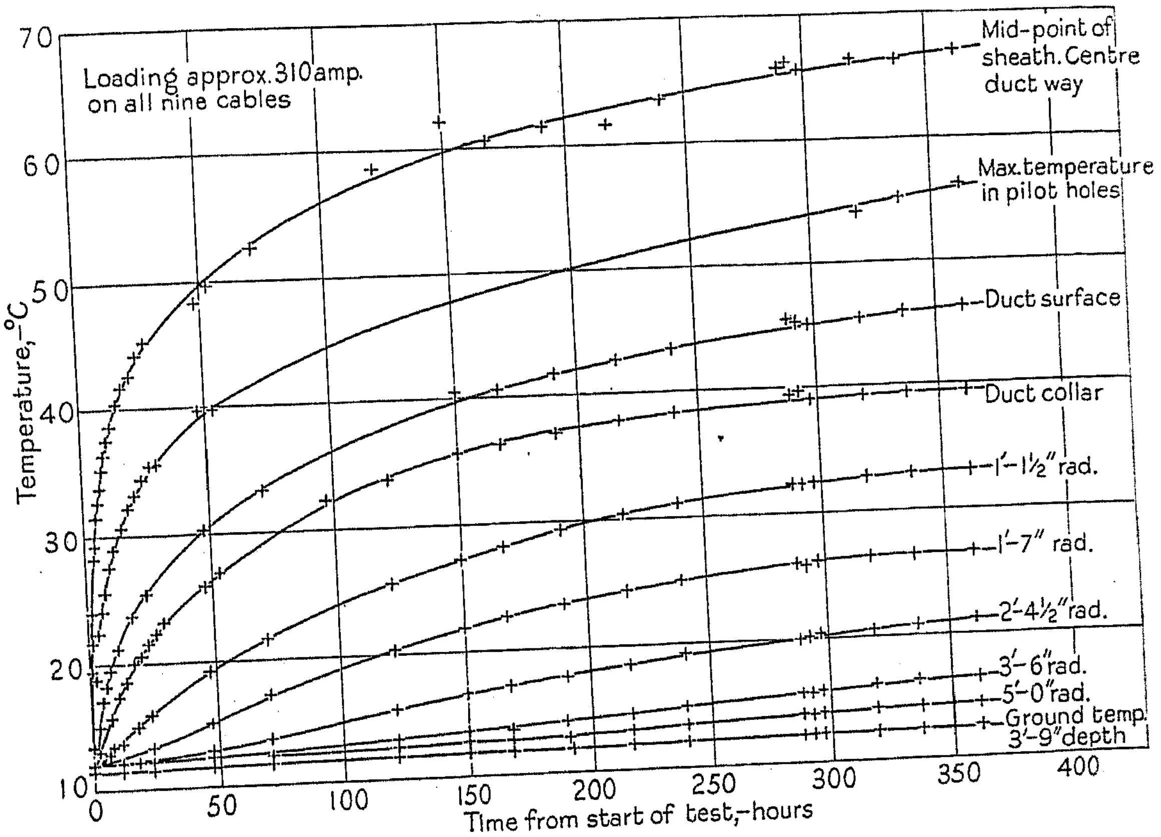


Fig. 22.—Temperature-rise on cable sheath and of the ground at the same depth as, and various distances from, the duct axis.

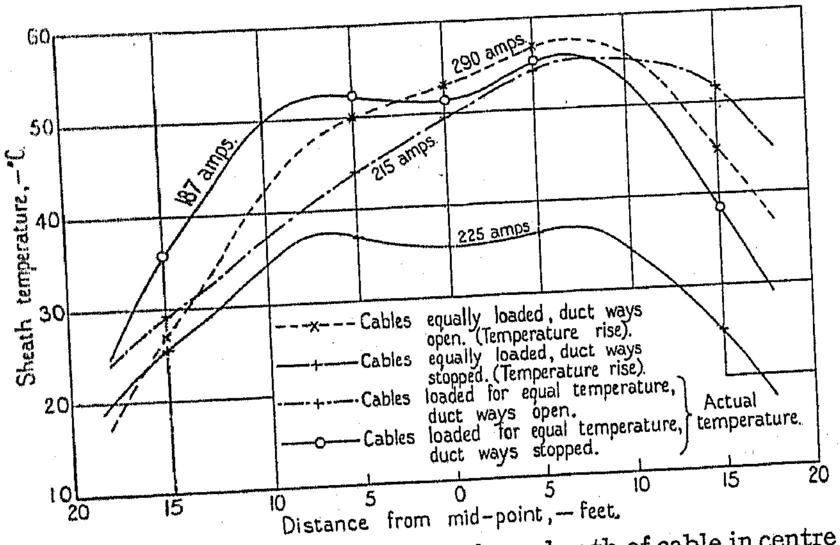


Fig. 23.—Temperature gradient along sheath of cable in centre duct-way under various conditions, all nine cables loaded.

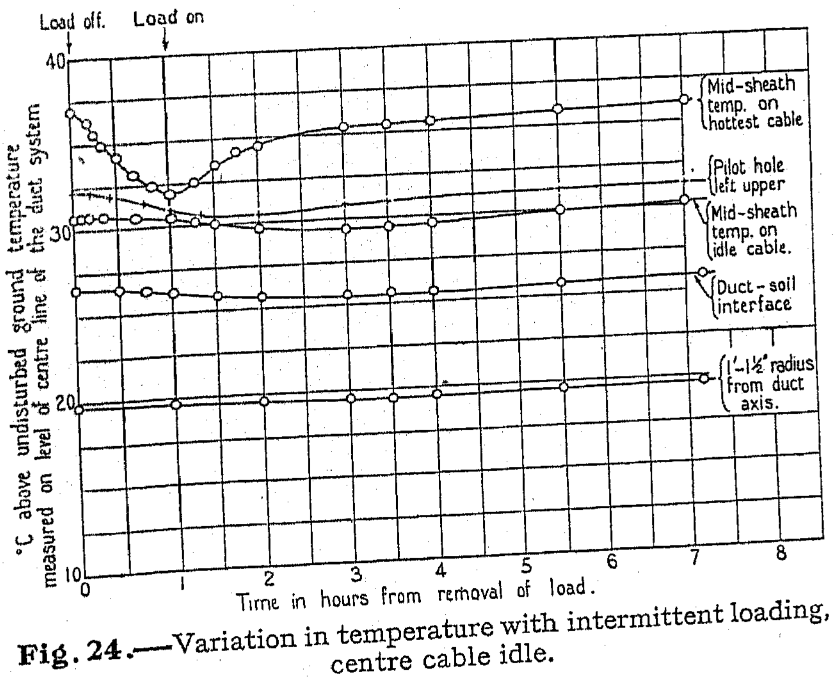


Fig. 24.—Variation in temperature with intermittent loading, centre cable idle.

As demonstrated in Appendix 2, alleviation of temperature-rise by longitudinal heat flow is negligible so long as the length of the duct system exceeds ten times the depth at which it is laid, even when there are large manholes at the ends, provided that longitudinal convection through the duct-ways is prevented. In the case of the tests described, therefore, it is legitimate to base the current rating on the mid-point temperature-rise.

Table 11

RELATIVE CURRENT IN EACH CABLE FOR GRADED LOAD TESTS

Position of duct-way		Relative current, per cent	
		All nine cables loaded	Middle cable idle
Bottom row	outers	100	100
	middle	90	95
Middle row	outers	80	70
	middle	70	nil
Top row	outers	90	90
	middle	75	85

Experiments made with the duct-ways stopped and open led to the conclusion that, though the latter condition would tend to increase the rating, the effect in practice was likely to be small except with short duct lines.

As regards grading the load, in the two cases investigated the current-carrying capacity of the duct system as a whole was increased by about 5 per cent by this

Table 12

THERMAL RESISTIVITY OF THE SOIL AND CURRENT RATING OF NINE 0·4 SQ. IN. CONCENTRIC PLAIN LEAD-SHEATHED PAPER-INSULATED CABLES INSTALLED IN A NINE-WAY EARTHENWARE DUCT, FOR VARIOUS CONDITIONS OF LOADING

Conditions		Date	Thermal resistivity of soil, °C. per watt per cm³	Current rating, amperes
All cables loaded ..	Equal loading .	October 1935	88	220
	Graded loading .	November 1934	98	215
Middle cable idle, remainder loaded	Equal loading	December 1934	102	215
		February 1935	79	250
	Graded loading	March 1935	79	260
Middle cable only loaded		July 1935	93	358

NOTE.—*Current rating* is based on a conductor temperature-rise of 35 deg. C. at the mid-point of the duct system:

(i) For equal loading, the temperature-rise taken was that of the hottest cable.

(ii) For graded loading, the temperature-rise of each cable was taken, the rating given being the average current of the loaded cables.

means. Such an increase scarcely warrants rating each cable according to its position in the duct.

Again taking into account the variation in thermal resistivity of the soil between individual tests, it appears that leaving the middle cable idle increases the current rating of the remainder by only about 5 per cent, and the current-carrying capacity of the duct system as a whole is therefore decreased by this means.

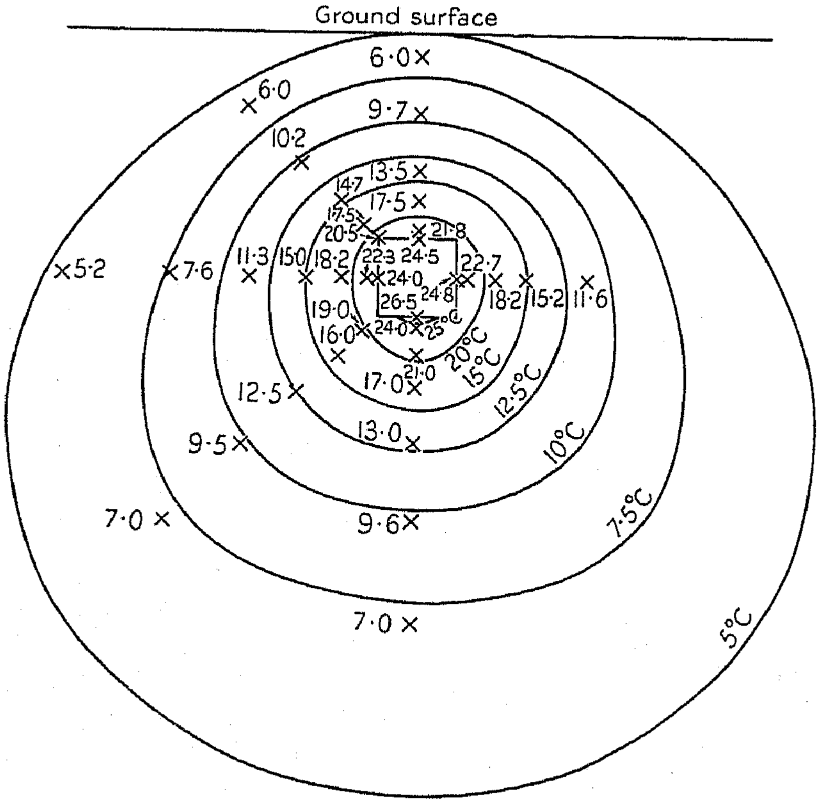


Fig. 25.—Temperature-rise in ground around 9-way duct system, with all cables equally loaded (225 amperes).

The thermal resistivity of the soil has already been mentioned, and experimental values determined in the course of the tests are included in Table 12. These values have been calculated from the temperature gradient in the soil surrounding the duct (Fig. 27) on the assumption that at a short distance outside the latter the heat-flow is uniform and radial. The results, although possibly not accurate, show a similar seasonal variation to that noted in Section (3), viz. a generally high value in the latter half of the year, reaching a maximum in the autumn, and followed by a sharp decrease about the end of the year, the low value being maintained until the spring, when it rises more gradually.

Table 13

THERMAL RESISTIVITY OF THE SOIL AT HARLESDEN

Month	Sphere tests, 1936		Cable tests, 1934–1935
	9-in. sphere °C./watt/cm³	3-in. sphere °C./watt/cm³	(Taken from Table 12) °C./watt/cm³
November ..	—	—	98
December ..	—	—	102
January ..	—	—	—
February ..	—	—	79
March ..	—	—	79
April	—	—	—
May	83	81	—
June	90	83	—
July	90	85	93
August ..	84	99	—
September ..	84	97	—
October ..	84	97	88
November ..	85	89	—
December ..	81	85	—

More precise tests using the buried-sphere method were subsequently carried out and confirmed the values previously obtained as well as could be expected, having regard to the non-uniformity of the soil and the fact that the investigations were not made simultaneously. The results showing seasonal variation are given in Table 13.

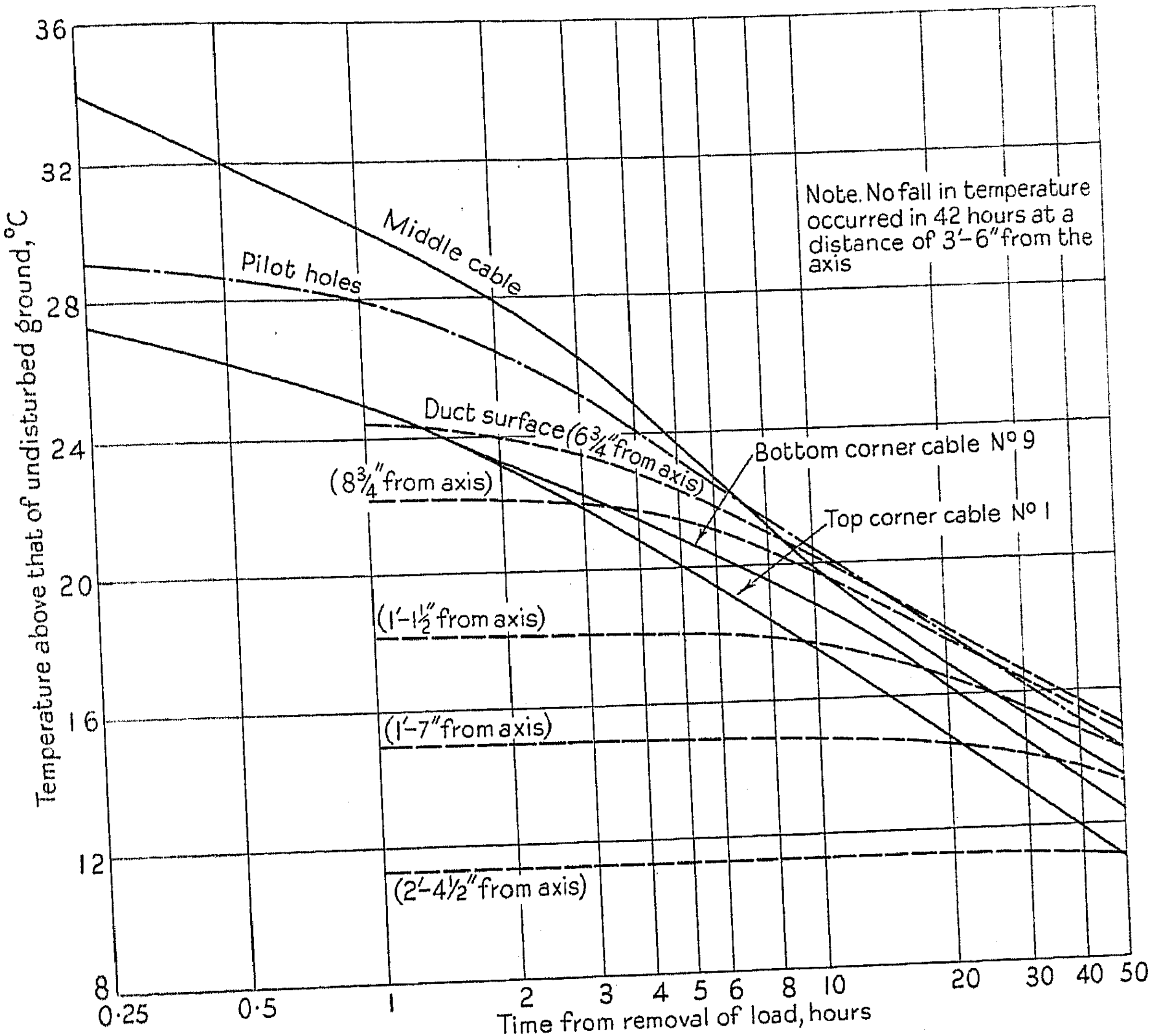


Fig. 26.—Fall of sheath, air, and soil temperatures on removal of load.

With regard to the effect of the duct system on the surrounding soil, on opening up the ground at the conclusion of the tests it was noticeable that drying out of the soil had occurred very irregularly, but in no case had the soil shrunk away from the duct wall. Samples were taken along the top surface of the duct where this irregularity was plainly discernible even by eye, in some cases the clay having formed hard, dry lumps, while in others it had remained moist and plastic. The results of moisture-content tests carried out by the National Physical Laboratory on these and other samples both in contact with, and remote from, the duct wall confirmed the visual observation, as shown in Table 14, the value for samples in close proximity to the duct varying between 19·7 and 37·8 per cent of the dry weight, while at a distance of 2 ft. from the duct and at the same depth the moisture content was 36·2 per cent.

Table 14

MOISTURE CONTENT OF CLAY SOIL TAKEN FROM HARLESDEN SITE IN VICINITY OF DUCT LINE

Sample	Position from which the sample was taken	Moisture content, percentage on dry weight
A	From a point 2 feet away from duct in same horizontal plane ..	36·2
B	From the layer of clay on top of the duct	25·5
C	From a point 2 to 3 inches above the duct	35·9
D	From the layer of clay on top of the duct	19·7
E	From the layer of clay on top of the duct	32·3
F	From the layer of clay in close proximity to side of duct	37·8

Samples B, D, and E were taken from points spaced about one foot apart along the length of the duct.

The initial heating and final cooling curves shown in Figs. 22 and 26 follow mainly a logarithmic law with respect to time, although, of course, there is some time-lag in the early stages which is more pronounced as the distance from the duct increases. Ground temperatures at distances greater than 2 ft. from the duct are unaffected by even completely cutting off the load (or on first switching it on) within a period of two days. On the other hand the cables themselves attain about 60 per cent of their final temperature-rise (or fall by that amount) in the same time. It is of interest to note that after about 12 hours from switching off the load the heat flow between the duct surface and the cables is reversed.

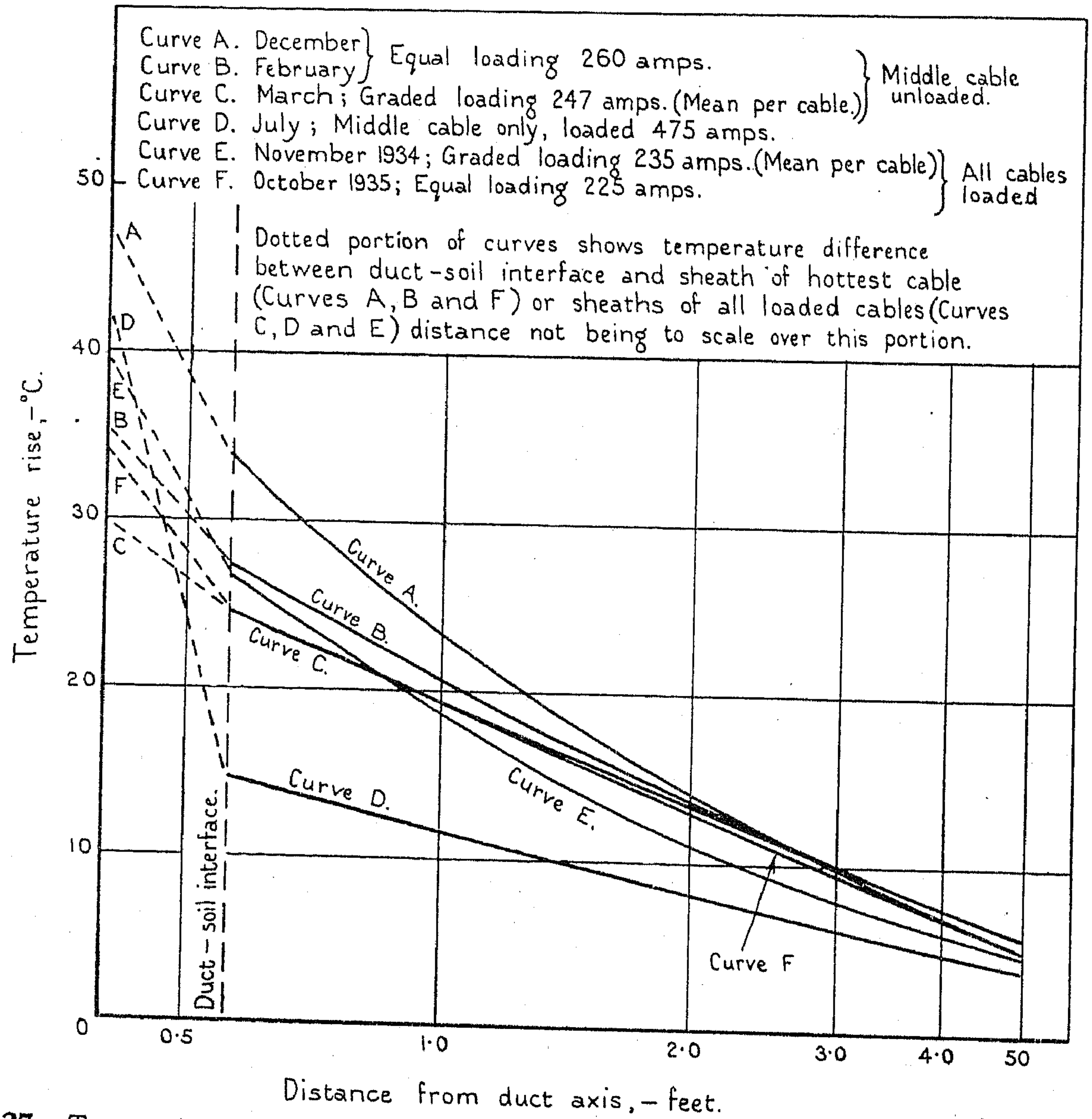


Fig. 27.—Temperature gradient for a 9-way duct system with all cables loaded, with centre cable unloaded, and with centre cable only loaded.

Some idea of the effect of intermittent loading can be gained from an examination of Fig. 24, in which is plotted the variation in temperature-rise which occurred on the cable sheaths, in the pilot holes, and at various points in the soil around the duct when the load was cut off for a period of one hour and then again switched on. The curves show that the maximum fall in sheath temperature was only 5 deg. C., i.e. 13·5 per cent of the initial steady value, during the period of no load, and that the temperature began to rise again immediately the load was restored, and was within 2 per cent of its initial value at the end of 6 hours. On the idle cable the maximum fall was only 1·4 deg. C. while at the duct-soil interface it was 1 deg. C. (4·5 per cent and 3·8 per cent respectively of the initial rise), these values occurring 3 hours after the load was cut off, and the temperature-rise in each case reaching within 2 per cent of its initial value 6 hours after restoring the load. At a radial distance of 1 ft. $1\frac{1}{2}$ in. from the duct axis the total variation was only 0·2 deg. C., i.e. 1 per cent of the initial steady rise.

(c) Correlation of Test Results with Theory

By using observed temperatures together with methods of computing the thermal resistance of each part of the heat path set out in Section (4)(*a*) of the paper, the total observed heat dissipation from the cable can in certain cases be compared with that which would be expected from theoretical considerations.

Three such cases have been examined as follows:—

(1) All nine cables equally loaded, with the duct-ways stopped at each end.

(2) Middle cable idle, remainder equally loaded, with all duct-ways stopped at each end.

(3) One cable only loaded, situated either in the middle or in one corner duct-way, with all duct-ways stopped at each end.

In the first case the observed temperatures of the middle cable sheath and of the soil at or near the outer surface of the duct (both in the horizontal plane of the duct axis and on its diagonal) have been used. The heat-flow diagram has been constructed (Fig. 21) by the method described in Section (4)(*a*), and the temperature scale deduced from the total observed dissipation from each cable and the thermal resistivity of the duct material which has been taken as 83·5° C./watt/cm^3. The temperature of the wall of the centre duct-way (assumed isothermal) and the temperature-difference between cable sheath and duct wall have thus been obtained. These values have then been used in calculating the loss by radiation, convection, and conduction, according to the methods set out in Section (4)(*a*) and the results are shown in Table 15 (*a*) and (*b*). The actual dissipation was 0·078 watt/cm. and the observed sheath temperature at the mid-point agrees with the theoretical dissipation assuming a minimum clearance of about 0·02 in. between cable sheath and bottom surface of the duct, while the observed maximum sheath temperature corresponds to a minimum clearance of about 0·3 in. These appear to be reasonable limits for a cable drawn in along the bottom of the duct, and the experimental results can be said to agree with theory. Further theoretical support for the experimental results has been obtained by determining the mean temperature of each of the outer duct walls from the heat-flow diagram and adding the temperature-difference between duct wall and cable sheath on the assumption that the thermal resistance of this portion of the heat path lies between the limits deduced from the observed temperature of the middle cable, viz. 54 and 93° C./watt/cm. The resulting values of sheath temperature-rise are compared with those actually observed in Table 16 and are seen to agree reasonably well.

Table 15(a)

HEAT TRANSFER FROM CABLE SHEATH TO INNER WALL OF DUCT

Temperature of sheath at mid-point, 47° C.
Temperature of inner wall of duct, 42·8° C.

Minimum clearance between sheath and bottom of duct-way, inch	Radiation, watt/cm.	Convection, watt/cm.	Conduction, watt/cm.	Total transfer, watt/cm.	Thermal resistance from sheath to duct, °C./watt/cm.
0·86*	0·0242	0·0074	0·0098	0·0414	102
0·1	0·0242	0·0052	0·0206	0·0500	84
0·05	0·0242	0·0052	0·0284	0·0578	73
0·02	0·0242	0·0052	0·0448	0·0742	57
0·01	0·0242	0·0052	0·0602	0·0896	47

* Concentric

Table 15(b)

HEAT TRANSFER FROM CABLE SHEATH TO INNER WALL OF DUCT

Maximum temperature of sheath, 50° C.
Temperature of inner wall of duct, 42·8° C.

Minimum clearance between sheath and bottom of duct-way, inch	Radiation, watt/cm.	Convection, watt/cm.	Conduction, watt/cm.	Total transfer, watt/cm.	Thermal resistance from sheath to duct, °C./watt/cm.
0·86*	0·0415	0·0147	0·0168	0·0730	98
0·4	0·0415	0·0147	0·0197	0·0758	95
0·1	0·0415	0·0103	0·0353	0·0871	83

* Concentric.

In the second case, in which the middle cable was idle, a similar method has been adopted. The sheath temperature-rise deduced is compared with that observed in Table 16, the corresponding values again agreeing closely.

Construction of the heat-flow diagram for the case in which the middle cable only was loaded (Fig. 20) reveals a considerable discrepancy between the observed temperature-drop from the sheath to the outer wall of the duct cluster and that deduced from the diagram, assuming the same thermal resistivity of duct material and thermal resistance from the sheath of this cable to the duct wall as before. This discrepancy is probably due to the assumption made in constructing the diagram that no heat flows across the duct-ways containing idle cables, since these duct-ways are in fact partly filled by good

Table 16

MID-POINT TEMPERATURE-RISE OF INDIVIDUAL CABLE SHEATHS

	All nine cables equally loaded		Middle cable idle, remainder equally loaded	
	From heat-flow diagram, deg. C.	Observed,* deg. C.	From heat-flow diagram, deg. C.	Observed,* deg. C.
Centre duct-way	34	34	30	30
Outer middle duct-way ..	29·5–32·5	31–33	34–38	35–36·5
Outer corner duct-way ..	27–30	28–29	32·5–36·5	33·5

* Neglecting cables affected by water flow through bottom row duct-ways.

heat conductors which are not themselves emitting heat, and which will therefore tend to provide a path parallel to that through the duct material. The assumption that no heat passes across the pilot holes may still be made.

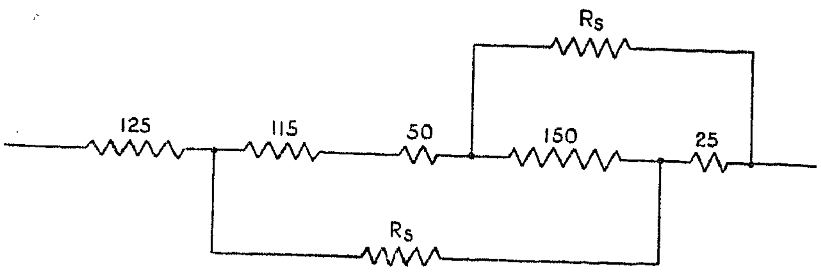
Table 17

TOTAL THERMAL RESISTANCE FROM CONDUCTOR OF A CABLE IN A DUCT-WAY TO SURFACE OF GROUND, AND LOAD ON THAT CABLE FOR 35 DEG. C. RISE OF CONDUCTOR

0·4 sq. in. 600-volt concentric plain lead-sheathed cable.
Earthenware ducts ($g_d = 83{\cdot}5°$ C./watt/cm³), internal diameter of duct-ways = 3½ in., axial spacing between duct-ways = 4½ in.
Depth to axis of duct cluster = 100 cm.
Thermal resistivity of soil = 90° C./watt/cm³

	Single-way duct (thickness of duct wall = ¾″)	Centre cable in a nine-way duct cluster			Any cable in a four-way duct cluster, four cables equally loaded
		Centre cable only loaded		All cables equally loaded	
		Assuming no heat-flow through other duct-ways	Corrected for heat-flow through other duct-ways		
Thermal resistance, deg. C./watt/cm.:					
Core to sheath	30	30	30	30	30
Sheath to inner wall of duct	54	54	54	54	54
Inner wall of duct to radius R_e	5	59	26	87	11
Radius R_e to ground surface	50	34	34	302	156
Total	139	177	144	473	251
Loading, watts/cm.:					
From above	0·252	0·198	0·243	0·074	0·139
Observed	—	0·238		0·075	—
Loading, amperes:					
From above	405	360	400	220	300
Observed	—	395		220	—

An approximate correction for this effect can be made by considering the analogous electrical resistance network. The main heat path (through the duct material) can be represented by a number of resistances in series, the values assigned to each being determined from the heat-flow diagram. Two shunt paths are then introduced to represent the two duct-ways carrying idle cables. The approximate points in the main path across which these shunt resistances are tapped are determined by inspection of the heat-flow diagram, and the values assigned to the shunt resistances are alternatively 100 ohms and 200 ohms, being approximately twice the values previously calculated for the thermal resistance of the air within a duct-way (since only one-half of the duct-way is covered by the diagram), when the minimum clearance between cable and duct wall is 0·01 in. and when the cable is concentric with the duct-way respectively. The resultant values for the resistance of the network (shown in Fig. 28) are 209 ohms and 226 ohms respectively, and the thermal resistance of the whole duct section may be deduced as lying between limits of 26·1 and 28·3° C./watt/cm. The experimental results gave a value of 25·8° C., which is thus in very satisfactory agreement.



R_S= resistance across duct-way containing idle cables.

Fig. 28.—Equivalent resistance network for 9-way duct with middle cable only loaded.

Neither strict mathematical nor graphical methods can be applied when a single loaded cable is situated in a corner duct-way of a multi-way cluster. Some idea of the total thermal resistance under these circumstances can, however, be obtained by comparing the value found above for the middle cable with that calculated for a similar cable in a single-way duct of the same internal diameter, since for a cable in any outer duct-way the total thermal resistance will clearly lie between these limits. Table 17 shows that there is very little difference between the two cases provided that, when the loaded cable is in the middle duct-way, some heat is assumed to flow across those containing idle cables as provided for above.

The various components of the thermal resistance, and the permissible loading for a conductor temperature-rise of 35 deg. C. for some of the conditions under which tests were carried out, are given in Table 17. The results for a similar cable in a single-way duct and in a four-way duct having the same internal diameter, spacing between duct-ways, and depth to duct axis are also given in Table 17.

Very little published data exists on this subject but Torchio* has stressed the importance of rating a cable according to the number of duct-ways and the position of the cable in the duct cluster. He gives the relative watt losses for a given temperature in each cable for multi-way duct clusters, expressed as a percentage of the permissible losses in a bank of two by two ducts. Unfortunately, the paper omits to give particulars as to the internal thermal resistance of the cable, ratio of cable diameter to duct diameter, ratio of duct diameter to duct spacing, depth of laying the duct system, and thermal resistivity of duct material and soil. These are essential for comparison with the results of the present investigation. Table 18 gives a comparison between Torchio's figures for a 9-way duct and those of the authors expressed as a percentage of the permissible loading (in watts) of the cables in the corner duct-ways, mean values being taken in the latter case. It is improbable, however, that the two sets of figures are strictly comparable.

Table 18

RELATIVE LOSSES IN WATTS FOR A GIVEN TEMPERATURE, ON EACH CABLE IN A 9-WAY DUCT CLUSTER

	Torchio	E.R.A.
Outer corner duct-ways ..	100	100
Outer middle duct-ways ..	85	73
Centre duct-way	69	55

The latest American data* are much more complete, ratings being given for cables of all sizes and of various types and voltages when run in air and when installed in ducts carrying 3, 6, 9, and 12 cables, in the latter case only the outer duct-ways containing loaded cables. The conditions corresponding most nearly to those of the present investigation relate to a 700 000 circular-mil (approx. 0·55 sq. in.) 7 500-V concentric cable, and the current ratings, assuming equal loading of all cables, expressed as percentages of those for the same cables run singly in air at the same temperature-rise, are compared in Table 19. The percentage reduction factors deduced from the data referred to above would be very little affected by the difference in size and voltage in the two cases.

Table 19

CURRENT RATING OF CONCENTRIC CABLES LAID IN DUCTS EXPRESSED AS A PERCENTAGE OF THAT FOR THE SAME CABLES IN AIR

	No. of cables in duct					
	3	4	6	8	9	12
U.S.A. (700 000-circ. mil 7 500-volt cable) ..	75%		67%		61%	56%
E.R.A. (0·4-sq. in. 660-volt cable)	68%	64%		49%		

It appears therefore that the reduction due to laying in ducts as found by the authors is greater than that provided for in other published data.

(5) CABLES IN AIR

(a) External Thermal Resistance

From a large number of tests on various cables in various configurations, made at the N.P.L., it has been deduced that the total thermal dissipation from the surface of cable in air may conveniently be expressed as $Ah\theta_s^{5/4}$, where A is the surface area in cm.^{2} per cm. length, θ_s the temperature-rise in deg. C. of the cable surface, and h a constant embodying convection, radia-

---

* See Bibliography, (22).

* See Bibliography, (23).

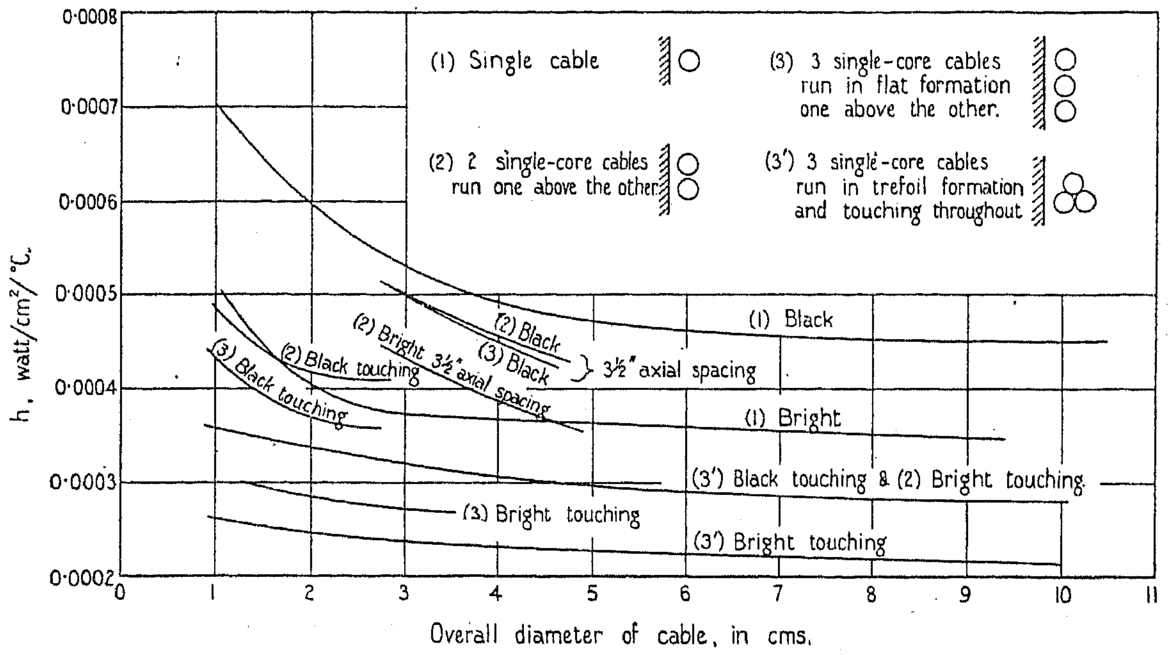


Fig. 29.—Curves showing the constant of heat emission h for both black and bright surfaces.

tion, conduction, and mutual heating in watts per cm² per °C. Values of h for various configurations are shown in Fig. 29. The external thermal resistance G_A is then given by

$$G_A = 1/\pi d h \theta_s^{1/4} \quad . \quad . \quad . \quad . \quad (13)$$

where d is the diameter of the cable and θ_s the surface temperature-rise; θ_s can be found exactly by solving the equation

$$(1 + \lambda)(\theta_c - \theta_s) = \pi d h \theta_s^{5/4} G' . \quad . \quad (13.1)$$

This was done in a number of typical instances, and mean values for θ_s were thereby deduced. These are shown in Table 20.

Table 20

Type of cable	2 single-core L.V. cables D.C.			2 single-core L.V. cables A.C.		3 single-core cables 1 and 3 kV A.C.		3 single-core cables 20 kV		3-core belted 1 and 3 kV			3-core belted 20 kV		
Core temp.-rise, deg. C. ..	45			45		45		40		45			30		
Surface temp.-rise, deg. C. ..	36·2 *a*	32·2 *b*	28·6 *c*	35·4 *a*	31·5 *b*	37·1 *a*	34·1 *b*	29·2 *a*	26·9 *b*	34·5 *a*	30·5 *b*	28·5 *c*	18·3 *a*	16·7 *b*	15 *c*

a = Sheath of plain lead-covered cable. *b* = Serving of unarmoured cable. *c* = Serving of armoured cable.

Table 21

Ambient temperature, °C.	25	30	35	40	45
Cables with 70° C. maximum temperature	1·00	0·93	0·87	0·80	0·72
Cables with 65° C. maximum temperature	1·00	0·93	0·85	0·77	0·68
Cables with 55° C. maximum temperature	1·00	0·90	0·80	0·68	0·54

These mean values were inserted in equation (13), whence, with the curves for h, the values of G_A were determined and used in the fundamental equation (1).*

Braided and served cables behave as black bodies to a sufficient approximation. Plain lead-sheathed cables when new have small emissivities which increase with age. If the surface is treated then the black-body assumption may usually be made (see Table 8).

Cables run in air experience usually only the normal tarnishing, and after a consideration of tests on cables and materials, it was decided to take the mean of the values for h for "black" and "bright" cables, this assumption having been found to give the best agreement.

---

* Lythgoe [see Bibliography, (30)] adopts a constant value of 0·0009 for h, the final result, however, not being very different.

As shown elsewhere,* the effect of change of ambient temperature is susceptible of a simple approximation. For the standards herein adopted this leads to the rating factors shown in Table 21.

Cables exposed to the sun are liable to an increased temperature-rise on account of the solar radiation absorbed. It is therefore desirable to shield cables from the sun without at the same time restricting ventilation, which is a natural advantage of outdoor situations. The matter is rather complicated for generalization and reference should be made to more detailed reports.†

Table 22

RATING FACTORS FOR VARIOUS COVERINGS LAID DIRECT AND RUN IN AIR

Type of cable	Direct in ground (*b*)			In air		
	Up to 0·30 sq. in.	0·30 to 0·50 sq. in.	Above 0·50 sq. in.	Up to 0·30 sq. in	0·30 to 0·50 sq. in.	Above 0·50 sq. in.
Concentric and triple concentric	1·03	1·03	1·03	(*a*) 0·96 (*b*) 0·99 (*c*) 0·99	0·97 0·98 0·98	0·97 0·97 0·98*
Twin a.c.	1·03	1·04	1·05†	(*a*) 0·96 (*b*) 0·98 (*c*) 0·98	1·00 1·01 1·00	1·01‡ 1·02§ 1·00
D.C.	1·03	1·03	1·03	1·00	1·00	1·00
3-core and 4-core	1·03‖	1·05¶	1·07**	(*a*) 0·96 (*b*) 0·98‡‡ (*c*) 0·98¶¶	1·01 1·02§§ 1·00	1·03†† 1·04‖‖ 1·00
Single-core cables, (*a*) only	Two only			0·93	1·00	1·00
	Three cables in trefoil			0·92	0·95	0·96
	Three cables transposed in same plane			0·95	0·98	1·01
	As above but untransposed			0·95	1·01	1·06

* 0·99 above 0·75 sq. in.
† 1·04 for 3–10 kV.; 1·06 above 0·75 sq. in.
‡ 1·02 above 0·75 sq. in.
§ 1·04 above 0·75 sq. in.
‖ 1·02 for 20 kV.
¶ 1·04 for screened cables.
** 1·10 above 0·75 sq. in.
†† 1·05 above 0·75 sq. in.
‡‡ 1·01 for 10 and 20 kV.
§§ 1·03 for 10 and 20 kV.
‖‖ 1·07 above 0·75 sq. in.
¶¶ 0·99 for 10 and 20 kV.

(*a*) Plain lead. (*b*) Served unarmoured. (*c*) Bare wire-armour.

(b) Time-Constant

The work of Melsom and Booth,‡ and earlier E.R.A. work,§ shows that a cable in air rapidly attains its final temperature, such that no allowance can be made for the intermittent or cyclic loads hitherto considered. For shorter periods an allowance may be made. For example, if $\sqrt{(S\theta_c/Rt)}$ exceeds the continuous rating, where t is the duration in sec., S the thermal capacity of the cable in joules per cm. length per deg. C., this expression may be used in place of the normal continuous rating. For peak-hour loading equation (41) of Appendix 3 is reduced, by making S_e vanish as the air has little thermal capacity, to give

$$\theta_c(t)/\theta_c = \alpha^2(1 - e^{-t/SG}) \quad . \quad . \quad . \quad (9.11)$$

in place of equation (9.1) for cables laid direct, so that

$$\text{Maximum peak-hour load} = I\sqrt{(\alpha^2 + \alpha_0^2)}$$

$$= I\left[\alpha_0^2 + \frac{1 - \alpha_0^2}{1 - e^{-t/SG}}\right]^{1} \quad . \quad . \quad . \quad (9.31)$$

in place of equation (9.3) for cables laid direct. The resulting ratings are shown in Fig. 17. These are in substantial agreement with the values given by Melsom and Booth,* who followed the same method. Experimental confirmation has been obtained by these authors and, more recently, by the E.R.A.† The more usual case is of an underground system terminated by cables in air, usually single-core tails or short runs. The continuous carrying capacity of these may be considerably greater than that of the underground sections, but since the peak rating factor will usually be much less, the cables in air may determine the peak loading of the system and not the underground cables.

(6) RATING TABLES AND CONCLUSIONS

The ratings deduced as in the foregoing are tabulated at the end of the paper (see pages 552 to 557). They refer to served but unarmoured single-core cables and to served and armoured multi-core cables. For cables laid direct the omission of the armouring alters the thermal resistance and the losses. For cables in air the emissivity of the covering must also be taken into account. Table 22 gives the rating factors by which the appropriate rating may be derived from the tabulated values.

---

* See Bibliography, (6).
‡ *Ibid.*, (3).
† *Ibid.*, (29).
§ *Ibid.*, (1).

* See Bibliography, (24).
Ibid., (28).

With ducts the maximum temperature is less for unarmoured than for armoured cables, and Fig. 30 shows the corresponding factors. For small cables the type of construction has a small effect on rating, and the effect of design voltage is not material except insofar as the maximum temperature is affected. Similarly, whether the centre point is earthed or unearthed has an influence at most of a few per cent. Shaped conductors are of advantage for cables laid direct but not as regards cables in air or in ducts. Screened and S.L.-type cables have about the same rating, the better thermal dissipation in the latter being offset by the increased sheath losses. Similarly, with large single-core cables the increased sheath losses offset the advantage of conductor separation as compared with multi-core cables, while the a.c. losses in large multi-core cables are a disadvantage in comparison with concentric cables. If wide separations for phase isolation with single-core cables were required, special methods of sheath bonding would become desirable or necessary.

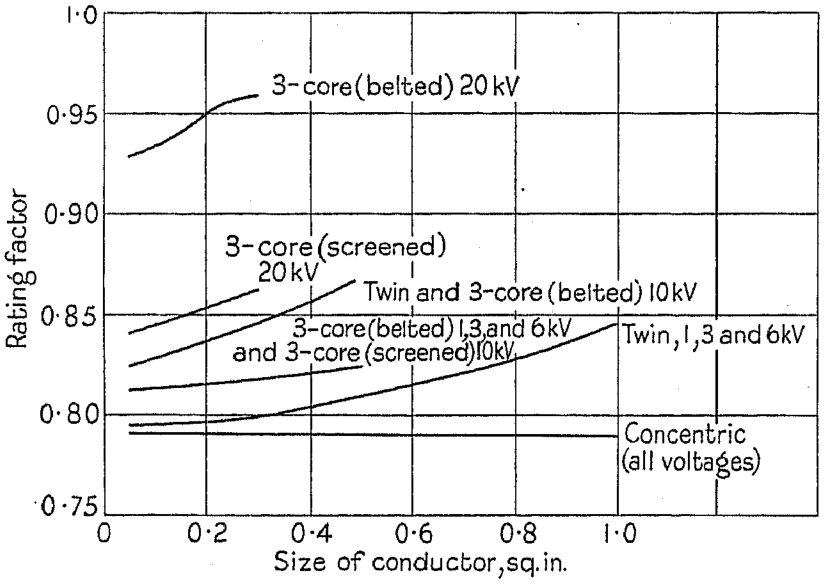


Fig. 30.—Rating factors for plain lead-sheathed cables in ducts.

The tables refer to cables laid in single-way ducts. Fig. 31 shows the factors by which these ratings must be reduced when several cables are laid in a multi-way duct, the diameter of the duct-way not being of great importance over the range commonly employed in practice.

With smaller cables the rating of a given cable is greater when laid direct than when run in air, but with larger cables the reverse is the case. The size at which the transition occurs varies with the type of cable, but it may be taken as roughly true, for the sizes most frequently employed, that where a cable line laid direct is terminated by a short run in air it will not usually be necessary to vary the size of cable. This conclusion must, of course, be modified according to special factors such as the grouping of cables, nature of covering, exposure to the sun, etc. Where, as is often the case, a multi-core cable laid direct is terminated by single-core tails run in air the rating of the tails will usually be considerably in excess of that of the multi-core cable.

The ratings for cables laid direct now put forward are greater than those in the previous Tables, but with alternating current the increase due to the increased temperatures is offset by the skin and proximity effects, and sheath and armour losses, now taken into account. The ratings for cables in air are substantially greater than the previous ratings, the investigations described herein having shown that the previous values were unduly conservative. With ducts, on the other hand, the present ratings are not only much less, particularly with unarmoured cables, than for cables otherwise installed, but are also less than the values previously used. This is largely due to the earlier underestimate of the thermal resistance in the duct-way and also to the taking into account of a.c. losses in the present Tables. Since, however, difficulties appear to be more frequently encountered with cables in ducts than when otherwise run, the decrease in rating should not be regarded as unduly conservative, although investigations in hand on the causes of these difficulties will, it is hoped, lead to an amelioration in the position.

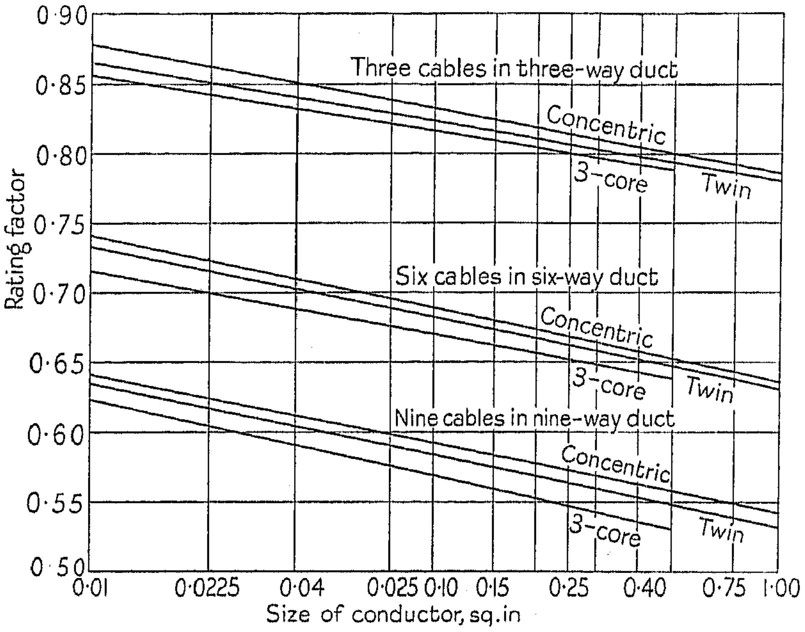


Fig. 31.—Rating factors for multi-way ducts (excluding single-core cables). Size of duct-way = 4 in. or 5 in.

Ratings for cables in the U.S.A. (Edison Electric Institute) are only given for cables in ducts and in air. The British and American ratings for nine 3-core cables in a multi-way duct agree very closely for corresponding cable sizes, although the actual basis is not the same in all particulars. Thus a temperature-rise of 65 deg. C. is permitted for 4·5-kV cables in the U.S.A., as compared with 55 deg. C. in this country, while in the American tables cables are assumed to be in outside duct-ways only, the British rating being calculated for a 9-way duct. In addition the standard frequency adopted differs (60 and 50 cycles in the two cases). Correction for all these factors would give lower American ratings, but in view of uncertainty as to the American assumptions regarding resistivity of duct and soil materials, dimensions of ducts, and depth of lay, no precise comparison is possible. Comparing cables in air with the same temperature-rise, the U.S.A. figures for single-core cables are in reasonable agreement with the E.R.A. figures, although tending to be high on account of the assumption of open-circuited sheaths in the U.S.A. For multi-core cables the U.S.A.

figures are rather less than the E.R.A. values, the difference amounting to some 8 per cent for larger sizes. In general, one may say that the main differences between the U.S.A. and E.R.A. ratings can be ascribed to differences in the maximum and ambient temperatures and assumptions made as to the basic conditions of installation.

ACKNOWLEDGMENTS

The authors wish to record their appreciation to the E.R.A. for permission to publish this paper, to the Committees and Panel under whose direction the work was carried out, and in particular to Messrs. E. Fawssett and T. N. Riley, for their co-operation as chairmen of these Committees. They would also acknowledge the assistance of the N.P.L., and in particular Dr. A. H. M. Arnold and Mr. H. C. Booth, whose work is referred to in the paper. Finally, the authors would thank Mr. E. B. Wedmore, the Director of the E.R.A., for his advice and help in the preparation of the paper, Mr. F. W. Page of his staff for assistance in calculating much of the data, and Mr. L. H. Daniel who carried out part of the work on ducts.

BIBLIOGRAPHY

1. E.R.A. Report Ref. F/T12: *Journal I.E.E.*, 1923, vol. 61, p. 517.
2. E.R.A. Report Ref. F/T14 (published in book form).
3. S. W. Melsom and H. C. Booth: *Journal I.E.E.*, 1911, vol. 47, p. 711.
4. E.R.A. Report Ref. F/T2: *ibid.*, 1921, vol. 59, p. 181.
5. E.R.A. Report Ref. F/T15: *ibid.*, 1926, vol. 64, p. 161.
6. E.R.A. Report Ref. F/T115: *ibid.*, 1938, vol. 83, p. 497.
7. E.R.A. Report Ref. F/T55: *ibid.*, 1935, vol. 76, p. 299.
8. A. H. M. Arnold: *ibid.*, 1935, vol. 77, p. 49; also an unpublished E.R.A. Report.
9. J. C. Costello: *ibid.*, 1936, vol. 79, p. 595.
10. E. B. Wedmore, P. D. Morgan, and S. Whitehead: *ibid.*, 1929, vol. 67, p. 359.
11. A. H. M. Arnold: *ibid.*, 1929, vol. 67, p. 69.
12. F. W. Carter: *Proceedings of the Cambridge Philosophical Society*, 1926–27, vol. 23, p. 901; *ibid.*, 1927–28, vol. 24, p. 65.
13. E.R.A. Report Ref. F/T116.
14. R.L. Atkinson: *Transactions of the American I.E.E.*, 1924, vol. 43, p. 966.
15. D. M. Simmons: *Electric Journal*, vol. 29, p. 336, July 1932.
16. D. M. Simmons: *Transactions of the American I.E.E.*, 1923, vol. 42, p. 600.
17. H. Waddicor: *Journal I.E.E.*, 1935, vol. 76, p. 195.
18. E.R.A. Report Ref. F/S5.
19. E.R.A. Report Ref. F/T48.
20. P. D. Morgan and S. Whitehead: *World Power*, 1932, vol. 13, p. 350.
21. E.R.A. Report Ref. F/T65.
22. P. Torchio: *Transactions of the American I.E.E.*, 1921, vol. 40, p. 107.
23. Edison Electric Institute: Publication No. A14, July 1933.
24. S. W. Melsom and H. C. Booth: *Journal I.E.E.*, 1923, vol. 61, p. 363.
25. L. Bosone: *l'Elettrotecnica*, 1931, vol. 18, p. 2.
26. R. A. Brockbank and J. K. Webb: *Journal I.E.E.*, 1929, vol. 67, p. 337.
27. S. Whitehead: *Electrician*, 1927, vol. 99, p. 225.
28. E.R.A. Report Ref. F/T106.
29. E.R.A. Report Ref. F/T44.
30. W. H. Lythgoe: *Distribution of Electricity*, April, 1933, p. 1206.

APPENDIX I

Theory of Armour Losses

(a) Multi-core cables.

(*i*) *General.*

The losses in the armouring of a multi-core armoured cable arise partly from the currents induced by the magnetic flux which cuts the armour and partly from the losses in the steel, due to the magnetic flux which penetrates it. The first may be described as the eddy-current losses and the second as the hysteresis losses, although certain eddy-current losses should in a more accurate calculation be included in the second type.

In addition the eddy currents in the lead sheath exercise a screening effect on the magnetic field due to the cores. Let ${}_1\phi_0$ be the magnetic potential due to the eddy currents in the lead sheath at a point (r, θ) with respect to the centre of the cable and let m be $\omega/R_s 10^9$, where R_s is the resistance of the sheath in ohms per cm. Then

$${}_1\phi_0 = \frac{jm}{1+jm}\phi' \text{ to the first term} \quad . \quad . \quad (14)$$

where ϕ' is the magnetic potential due to the cores. Thus the modified field is $(1 + 2jm)\,\phi'/(1 + jm)$. Since m^2 is small compared with unity, the contribution of the field of the eddy currents to the losses in the armour may be ignored to the approximation here required.

(*ii*) *Eddy-Current Losses.*

At the surface of the armour the radial induction and the tangential magnetizing force are continuous. Since the steel is thin, this means that the radial flux is relatively unaffected by the permeability of the steel. Thus the eddy currents induced by the radial flux will arise as if the steel behaved as a non-magnetic metallic sheath, apart from the spiralling effect in the case of wire armouring. Neglecting this, the eddy-current losses are given by the same formula as for the lead sheath. This formula has been given in the text, namely:—

$$\frac{\text{Eddy-current losses at 50 cycles}}{\text{Core losses in all cores}} = 3\cdot 2\left(\frac{R_A}{R}\right)\left(\frac{c}{b}\right)^2\frac{1}{1+10\cdot 15R_A^2 10^{12}} \quad . \quad (15)$$

where c = axial distance of core from centre of cable.
b = mean radius of armour.
R_A = resistance of armour in ohms/cm.
R = resistance of single core in ohms/cm.

(*iii*) *Hysteresis Losses.*

The distortion of the field due to the eddy currents of Section (ii) is given by an equation similar to those of

Section (i), except that m_1 replaces m, where m_1 is $\omega/R_A 10^9$. Since R_A and R_s are of the same order the distortion due to the currents in the armour may similarly be neglected.

Let

ϕ_1 = magnetic potential inside armouring due to the steel.

ϕ = magnetic potential in the steel itself due to the steel.

ϕ_0 = magnetic potential outside armouring due to the steel.

ϕ' = magnetic potential of core currents.

$$\phi_1 = \sum_1^{\infty} A_n \frac{r^2}{b_1^n} \sin n\theta \quad . \quad . \quad . \quad (16.1)$$

$$\phi = \frac{\Sigma(A_n - B_n\alpha^n)(b_1/r)^n + (B_n - A_n\alpha^n)(r/b_2)^n}{1-\alpha^{2n}} \sin n\theta \quad (16.2)$$

$$\phi_0 = \sum B_n \frac{b_2^n}{r^n} \quad . \quad . \quad . \quad . \quad (16.3)$$

$$\phi' = -\sum 2I\frac{c^n}{r^n}\frac{\sin n\theta}{n} \quad . \quad . \quad . \quad (16.4)$$

b_1 = internal radius of armour.
b_2 = external radius of armour.
$\alpha = b_1/b_2$.

These equations satisfy the conditions that ϕ_1, ϕ, and ϕ_0 are continuous at $r = b_1$ and $r = b_2$ and that $\partial\phi_1/\partial\theta$, $\partial\phi/\partial\theta$, $\partial\phi_0/\partial\theta$ are also continuous, which means that the tangential magnetizing field is continuous. In addition, the normal induction is continuous, giving

$$\text{at } r = b_1 \qquad \frac{\partial(\phi_1 + \phi')}{\partial r} = \mu\frac{\partial(\phi + \phi')}{\partial r} \quad . \quad . \quad . \quad (17.1)$$

$$\text{at } r = b_2 \qquad \frac{\mu\partial(\phi + \phi')}{\partial r} = \frac{\partial(\phi_0 + \phi')}{\partial r} \quad . \quad . \quad . \quad (17.2)$$

From these two equations A_n and B_n can be found as—

$$A_n = \frac{2(\mu-1)I}{n}\left(\frac{c}{b_1}\right)^n \frac{\mu+1}{1+\left[2\mu(1+\alpha^{2n})/(1-\alpha^{2n})\right]+\mu^2} \quad . \quad (18.1)$$

$$B_n = \frac{2(\mu-1)I}{n}\left(\frac{c}{b_1}\right)^n \frac{\alpha^n(\mu-1)}{1+\left[2\mu(1+\alpha^{2n})/(1-\alpha^{2n})\right]+\mu^2} \quad . \quad (18.2)$$

μ = permeability.

The radial induction in the steel differs little from the aerial induction, whereas the tangential induction is of the order of μ times the aerial induction. Thus, as is otherwise obvious, the tangential induction is much greater and need only be taken into account.

Substituting for A_n and B_n, the tangential induction in the steel is given by

$$\sum \frac{2\mu I}{r}\left[\frac{c^n}{r^n} - (\mu-1)\left(\frac{c}{b_1}\right)^n \times \frac{\left\{(\mu+1)-(\mu-1)\alpha^{2n}\right\}\frac{b_1^n}{r^n} + \left\{(\mu-1)-(\mu+1)\right\}\frac{r^n}{b_2^n}\alpha^n}{(1-\alpha^{2n})\left[1+2\mu\left\{(1+\alpha^{2n})/(1-\alpha^{2n})\right\}+\mu^2\right]}\right] \cos n\theta \quad . \quad . \quad . \quad (19.1)$$

If the thickness δ of the steel is small—

$$\alpha = 1 - (\delta/b)$$
$$\alpha^n = 1 - (n\delta/b)$$

and equation (19.1) reduces to—

$$\frac{2\mu I}{r}\sum\left[\left(\frac{c}{r}\right)^n - (\mu-1)\left(\frac{c}{b_1}\right)^n \frac{\left(1+\frac{n(\mu-1)\delta}{b}\right)\left(\frac{b_1}{r}\right)^n - \left(1-\frac{n\delta}{b}\right)\left(\frac{r}{b_2}\right)^n}{\frac{n\delta}{b} + 2\mu\left(1-\frac{n\delta}{b}\right) + \mu^2\frac{n\delta}{b}}\right]\cos n\theta \quad . \quad (19.2)$$

Again we may put $r = b$, where $b = \sqrt{b_1 b_2}$, and obtain—

$$\sum\frac{2I\mu}{b}\left(\frac{c}{b}\right)^n\left[1 - (\mu-1)\frac{n\delta/b}{\left\{2+(n\mu\delta/b)\right\}}\right]\cos n\theta$$

$$= \sum\frac{2I\mu}{b}\left(\frac{c}{b}\right)^n \frac{2+(n\delta/b)}{2+(n\mu\delta/b)} \cos n\theta \text{ approx.} \quad . \quad . \quad (19.3)$$

For simplicity only a single loaded core has been considered, but equation (19.3) can be made to apply to any number by addition. Remembering, however, that the series converges fairly rapidly and that a relatively minor effect is being considered, it is observed that equation (19·3) shows the induction in the steel to be roughly $\mu/[1 + n\mu\delta/(2b)]$ times the field due to the cores. In conditions similar to those envisaged here it has been found that the loss can be considered as an added resistance, that is, the hysteresis loss is proportional to the square of the flux density, as occurs at low field strengths. The field due to the cores is roughly $0\cdot3\sqrt{2}Ic/b^2$ max. in gauss if I is in amperes, so that the hysteresis loss is given by

$$P = 2\pi b\delta f 2\eta\left(\frac{0\cdot3I}{b}\frac{c}{b}\frac{\mu}{1+(\mu\delta/2b)}\right)^2 10^{-7} \text{ watts/cm.} \quad (20.1)$$

f is 50 and η is 0·001 for the class of steel commonly employed and c/b is 0·5 for most of the cables under consideration. Thus equation (20.1) reduces to (for a 3-core cable)—

$$\frac{\text{hysteresis loss}}{\text{core loss in all cores}} = \frac{0\cdot00046}{R10^6}\left(\frac{\delta}{b}\right)\left\{\frac{\mu}{1+(\mu\delta/2b)}\right\}^2 \quad (20.2)$$

where R = resistance of one core in ohms/cm.

The eddy currents which flow along the inside of the steel and return on the outside are neglected since the steel is thin.

(b) Single-core cables.

It has been stated in the text that single-core cables armoured with non-magnetic material may be employed with alternating current, but not if armoured with steel. It is therefore of some interest to quote means of calculating the losses in the former case and to give data on the latter to indicate the magnitude of the losses and consequent disadvantages which have led to its abandonment.

The sheath and armour losses in a system of three single-core cables in trefoil formation armoured with non-magnetic material and carrying 3-phase current, is given by an equation similar to equation (3.3), namely—

$$\lambda = \frac{\omega^2 M^2 R_{s1}}{R\left\{R_{s1}^2 + \omega^2(s_1 + M)^2\right\}} \quad . \quad . \quad . \quad (21)$$

where $M = 2 \log (2s/d) 10^{-9}$ H/cm.

$S_1 = LR_s^2/\left\{(R_s + R_A)^2 + \omega_2 L^2\right\}$

$$R_{s1} = \frac{R_s\left\{R_A(R_s + R_A) + \omega^2 L^2\right\}}{(R_s + R_A)^2 + \omega^2 L^2}$$

R_s = resistance of sheath in ohms/cm.

R_A = resistance of armour in ohms/cm.

L = self-inductance of armour due to spiralling.

S = spacing.

d = sheath diam.

r = radius of core.

For wire armouring

$$L = \pi^2 n^2 d_1^2 10^{-9} \text{ H/cm.} \quad . \quad . \quad . \quad (21.1)$$

where n = number of turns per cm in lay.

d_1 = diam. of armour.

For tape armouring

$$L = \delta\pi^2\left\{d_1/2(\beta + \gamma)\right\}^2 10^{-9} \text{ H/cm.} \quad . \quad (21.2)$$

where β = breadth of tape.

γ = distance between successive laps.

Normally the effect of the armour is to increase the losses by reduction of the effective sheath resistance, but with copper tape this effect may be made small by using a narrow tape and small gaps between turns such that the self-inductance L is high, and the resistance also high though to a less degree. For example, with a 0·04 in. thick copper tape ½ in. wide wound with a small gap between turns very little increase in sheath losses will occur for cables of 0·2 sq. in. distance. Better mechanical protection is obtained with bronze, since in addition its resistivity is higher and it can be used thicker than the copper. Similarly, thick layers or several layers of non-magnetic steel can be employed.

With wire armouring the inductance is not likely to be important without winding in so short a lay as to be inconvenient and mechanically weak. Thus

$$S_1 = L(R_{s1}/R_A)^2; \quad R_{s1} = R_s R_A/(R_s + R_A) \quad (21.3)$$

$$\lambda = \frac{R_{s1}}{R}\,\frac{\omega^2 M^2}{\left\{R_{s1}^2\left[1 + (\omega L/R_A)^2\right] + \omega^2 M^2\right\}}$$

$$= \frac{R_{s1}}{R}\,\frac{\omega^2 M^2}{(R_{s1}^2 + \omega^2 M^2)} \quad . \quad . \quad . \quad . \quad . \quad . \quad (22)$$

provided R_A is large enough. It is then clear that the loss varies roughly inversely as the resistance of combined sheath and armour and the resistance of the armour must be as large as possible compared with that of the sheath to avoid increasing the losses.

Theoretically there is advantage in decreasing the resistance of the armour, if carried to a sufficient degree. If R_A is made small compared with R_s, and if $\omega^2 L^2$ is still small compared with R_s^2, then

$$S_1 = L \quad \text{and} \quad R_{s1} = R_s\left\{(R_A/R_s) + (\omega L/R_s)^2\right\} = \epsilon R_s$$

where ϵ is small.

Thus

$$\lambda = \frac{\epsilon\omega^2 M^2 R_s}{R\left\{R_s^2\epsilon^2 + \omega^2(L + M)^2\right\}} \quad . \quad . \quad (23)$$

Now, if $R_s\epsilon$ becomes less than ωM then λ will decrease as ϵ, or R_A, is decreased. To achieve such a condition it would be necessary to have a substantially continuous envelope of armour such that L is negligible and

$$\lambda = \omega^2 M^2 R_A/\left[R(R_A^2 + \omega^2 M^2)\right] \quad . \quad . \quad . \quad (24)$$

whence the losses in the armoured cable become less than that in the unarmoured cable when the resistance

Table 23

SHEATH AND ARMOUR LOSS AS PERCENTAGE OF CORE LOSS

Connection	Current, amp.	Cable F				Cable G				Cable H, intertwisted, touching
		Touching		18 in. spacing		Touching		18 in. spacing		
		Calculated	Measured	Calculated	Measured	Calculated	Measured	Calculated	Measured	Measured
Unbonded	100	1 390	1 620	1 390	1 486	51	68	51	62	25
	200	1 550	1 758	—	—	123	139	123	134	35
	250	1 500	1 660	1 500	1 663	—	—	—	—	—
	300	—	—	—	—	163	187	163	190	51
Sheath and armour bonded	100	379	365	388	390	135	153	227	238	105
	200	385	399	392	417	162	167	233	238	110
	250	387	419	—	—	—	—	—	—	—
	300	—	—	—	—	173	179	236	240	115
Sheath only bonded	100	605	582	626	611	110	157	228	266	84
	200	625	661	640	673	165	204	288	300	98
	250	625	685	—	—	—	—	—	—	—
	300	—	—	—	—	192	243	290	332	109

of the armour reaches a sufficiently low value, easily calculated, which is of the order of less than ωM. In practice so low a resistance would be too costly to achieve except with unusually wide spacings, when M has a correspondingly high value.

With steel-wire armoured cables the hysteresis and eddy-current losses are important, and it is then found that bonding the sheaths and armour as normal decreases the losses. This is due to the screening exercised by the sheath currents on the core currents which reduces the magnetic flux in the armour. A method of calculation given by Bosone* has been verified in some experiments made by the Standard Telephones and Cable Co., Ltd., for the E.R.A. Table 23 gives a comparison between experiment and calculation.

F and G were 0·5-sq. in single-core 33-kV cables. Cable F was armoured with 40 steel wires 0·128 in. diameter with a lay of 8·67 in., and G with 52 similar wires with a lay of 32 in. A considerable reduction in losses with increase of lay is observed.

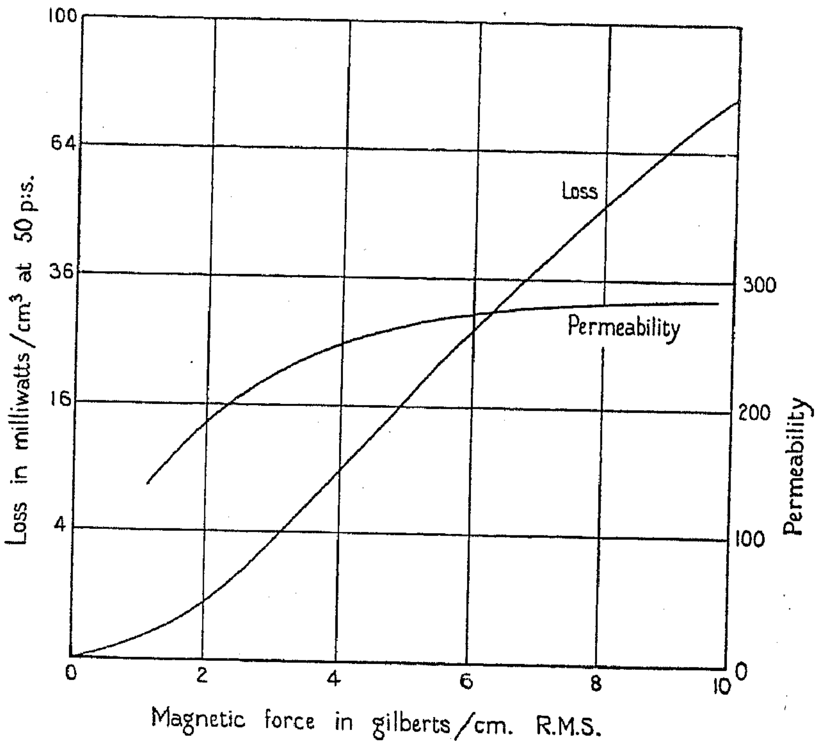


Fig. 32.—Magnetic properties of steel armour wires.

Brockbank and Webb† have shown that twisting three single-core cables together with the rotation of the barrel correctly related to the direction of armour lay, results in an increase in the effective lay and, therefore, should lead to reduced losses. This condition is specified in Table 23 as H (intertwisted) and shows a marked reduction in losses but mainly in the unbonded case.

Fig. 32 shows the magnetic properties of the steel wire used in the armour. It is seen that the permeability tends rapidly to a constant value close to 300, the value adopted in the text of the paper for computing armour losses in multi-core cables. It is also clear that the hysteresis and local eddy losses are substantially proportional to the magnetizing force, being approximately $0 \cdot 8H^2$ milliwatts per cm³ at 50 cycles, where H is the magnetizing force in gauss (r.m.s.). Taking the maximum permeability as 300 as shown, this gives

$$\text{Loss} = 0 \cdot 00088\, B^2_{max} \text{ ergs/cm}^3 \text{ per cycle}$$

The value adopted in the text for multi-core cables was 0·001 instead of 0·00088, an unimportant difference.

Fig. 33 shows some results from tests made for the I.E.E. Wiring Regulations Committee by the E.R.A., illustrating the effects in cables where they should also be large, namely, large low-voltage cables, in this instance two 0·75-sq. in. 1·5-kV single-wire armoured cables. As has already been noted, the main effect of bonding the sheaths and armour is to reduce the losses due to the screening action of the circulating currents.

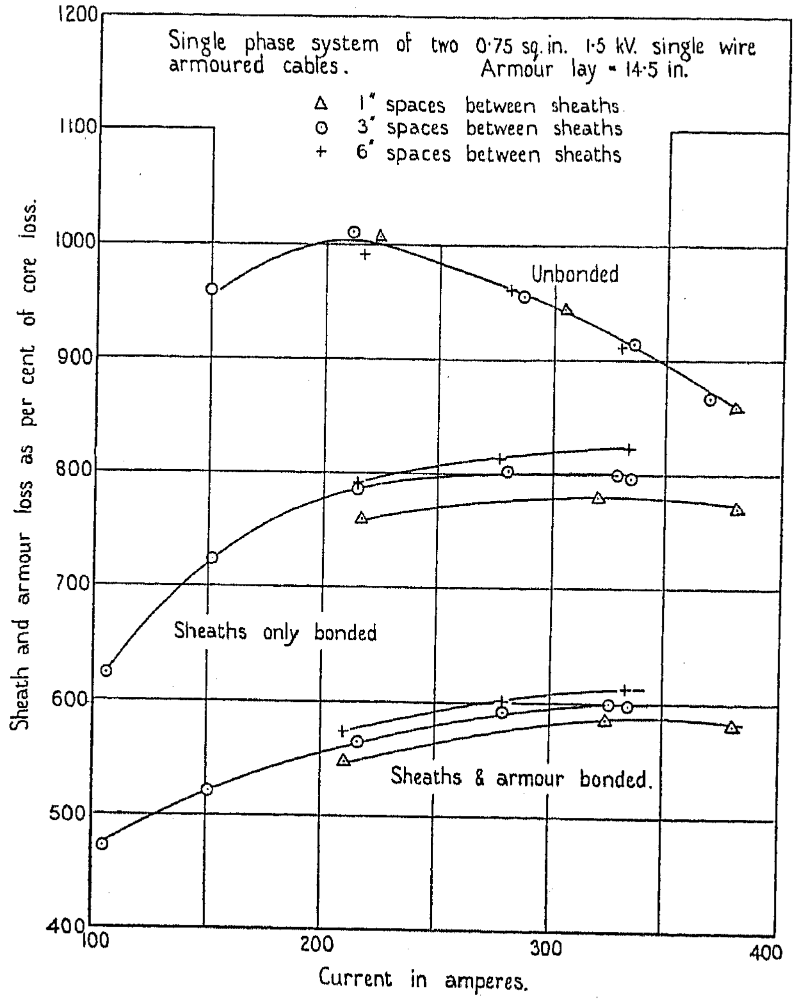


Fig. 33.—Sheath and armour loss in single-wire armoured single-core cables.

It is clear from the examples quoted that, even with such ameliorative devices as may be easily applied, the losses with single-core cables armoured with magnetic material are such as to preclude, in general, their use for alternating current. Apart from exceptional cases, the economical use of non-magnetic armouring requires a material of high electrical resistance, in addition to the required mechanical properties. It is, therefore, of interest to note the resistivities of possible materials as in Table 24.

Although, as has been mentioned, copper tape can be so applied as to give only a small increase in losses and although it has actually been employed in certain instances, yet it would appear that other metals should give more favourable results both from the aspect of reduction of losses and for mechanical protection. Bronze wires, particularly of the higher-resistance varieties, could be arranged to give small losses and much better mechanical protection. Even so, the resistance of bronze-wire armouring would be rather lower for normal lengths of lay. Brass does not offer any great advantages. The best results would seem to follow from the use of non-magnetic steel, the additional losses due to which could be made negligible, while it gives a high measure of mechanical protection. Unfortunately its cost is at present rather high. However, armouring is only desirable in certain circumstances, while an increased use might well result in a reduction of cost. The employment of non-magnetic steel is therefore worthy of consideration.

---

* See Bibliography, (25).

† *Ibid.*, 26).

The solution of (25) must be such that $(d\theta/dx)$ is zero when $x = 0$, and the solution of (26) must give θ as θ'_r when $x = \infty$. Both solutions must give the same values for θ and $(d\theta/dx)$ when $x = a$. The conditions are satisfied by the following solutions of (25) and (26):

$$\theta = \theta'_r - \frac{(\theta'_r - \theta_r)\, n \cosh n_1 x}{n \cosh n_1 a + n_1 \sinh n_1 a} \quad 0 < a < x \quad (27)$$

$$\theta = \theta_r + \frac{(\theta'_r - \theta_r) n_1 \sinh n_1 a}{n \cosh n_1 a + n_1 \sinh n_1 a} e^{-n(x-a)} \quad a < x < \infty \quad (28)$$

where $n^2 = (C/G)$ and $n_1^2 = (C/G')$

Table 24

RESISTIVITY OF ARMOUR MATERIALS

Material	Temperature	Resistivity, in microhms/cm. cube	Source
Copper (hard drawn)	40° C.	1·85	Various
Phosphor bronze	0° C.	5–10	Smithsonian Tables
Aluminium bronze	0° C.	12–13	Smithsonian Tables
Silicon bronze	0° C.	2·4	Van der Ven
Bronze	40° C.	8·5	Manufacturers
Bronze wires	20° C.	3·46	Tests for E.R.A.*
Brass (hard drawn)	0° C.	8·2	Siemens
Iron (pure)	0° C.	12·0	B.S.S. 115 (1924)
Steel E.B.B.	0° C.	10·4	Bureau of Standards
Steel B.B.	0° C.	11·9	Bureau of Standards
Steel, Siemens-Martin	0° C.	18	Bureau of Standards
Steel, tempered-soft	0° C.	15·9	Stronhal, Barus
Steel armour wires	20° C.	13·4	Tests for E.R.A.*
Non-magnetic steel	20° C.	77·6	Tests for E.R.A.*
No-Mag	20° C.	140	Ferranti catalogue

* Tests made for E.R.A. by Standard Telephones and Cables.

APPENDIX 2

Effects Due to Finite Length of System

(a) Longitudinal conduction in conductor and sheath.

Let the thermal resistance from conductor to the ambient temperature (surface of the earth) be G' for a long line of the type considered. Let the corresponding thermal resistance be G outside the line. Let W be the heat generated in the cable conductor, $2a$ the length of the line, and θ the temperature-rise of the conductor above ambient at a distance x from the middle of the line. If C_1 is the lengthwise thermal resistance per cm. of the conductor and C_2 the similar quantity for the sheath, then the longitudinal thermal conduction at x is:—$(1/C_1)(d\theta/dx) - (1/C_2)(d\theta/dx)$ towards the end. k is the ratio of the sheath to the conductor temperature-rise which can be taken as roughly constant for a given cable. If $C^{-1} = C_1^{-1} + C_2^{-1}$ the longitudinal conduction is $-(1/C)(d\theta/dx)$ and the variation of conductor temperature along the cable is given by:

$$-(G'/C)(d^2\theta/dx^2) + \theta = (WG') = \theta'_r \quad o < x < a \quad (25)$$

$$\text{and } -(G/C)(d^2\theta/dx^2) + \theta = (WG) = \theta_r \quad a < x < \infty \quad (26)$$

The maximum temperature-rise of the conductor θ_m is at the middle of the line $(x = 0)$ and is given by

$$\theta'_r - \theta_m = \frac{(\theta'_r - \theta_r) n}{n \cosh n_1 a + n_1 \sinh n_1 a} \quad (29)$$

Thus the actual alleviation in temperature $\theta'_r - \theta_m$ since θ'_r is the temperature-rise of a long line, is a fraction $n/(n \cosh n_1 a + n_1 \sinh n_1 a)$ of the maximum possible alleviation $(\theta'_r - \theta_r)$, which occurs if the line is of negligible length. In practice n_1 is usually greater than 0·01 so that the alleviation is not usually important for lengths of line greater than about 200 cm., so that no increase of rating due to this cause for a line of finite length can normally be allowed. Take for example a 0·15-sq. in. 3-core cable loaded with 220 amp., giving outside a section of high thermal resistance a temperature-rise of 50 deg. C. and inside the section a temperature-rise of 70 deg. C. If the section were 3 ft. long the alleviation due to finite length would be 9 deg. C., but if 10 ft. long it would be only 1·3 deg. C.

To determine the limiting error in an experimental line the temperature-rise is taken as zero outside the section considered. Accordingly (29) becomes:

$$(\theta_r' - \theta_m)/\theta_r' = \operatorname{sech} n_1 a$$
$$= 2e^{-n_1 a} \text{ if } n_1 a > 2 \text{ or } 3 \qquad (30)$$

Thus with lines of more than a few yards the error due to this cause is negligible since $n_1 a$ will be greater than 5. The error was negligible for the Harlesden duct line.

The analysis does not take into account the minor effect of the variation of the electrical resistance of the conductor with temperature. This is included if G is replaced by $G/(1 - \alpha G W_0)$, where α is the temperature coefficient of resistance and W_0 the heat generated in the conductor at ambient temperature and with the given current flowing. G' is similarly replaced by $G'/(1 - \alpha G' W_0)$.

(b) Longitudinal conduction of heat in soil and duct material.

The thermal resistivity of materials normally employed for ducts does not differ greatly from that of the earth. The thermal resistance from the cable to the duct wall is neglected, but since this is less affected by finite length than if dispersed in equivalent layers of the earth an approximation in excess is obtained. Thus cables for this connection may be considered as laid direct whether this is the case or whether ducts are employed.

If a cable of length $2a$ and depth l is assumed to behave as a line source of heat of strength W, then the temperature-rise θ_m at a point in the vertical plane through the centre of the line is:

$$\theta_m = W \log \left\{(r + a)(r' - a)/(r' + a)(r - a)\right\} \qquad (31)$$

where r is the distance of the point from the end of the cable and r' is the distance from the end of a similar cable formed by reflection in the surface of the earth—the image cable. If the duct is long then θ_m becomes θ_r', where $\theta_r' = 2m \log \rho/\rho'$, and ρ and ρ' are the perpendicular distances of the point from the cable and its image. Thus, substituting for ρ', r, and r':—

$$\theta_r' - \theta_m = -W \log \frac{\left[(a^2 + \rho^2)^{\frac{1}{2}} + a\right]\left[\left\{a^2 + (2l - \rho)^2\right\}^{\frac{1}{2}} - a\right]\rho^2}{\left[(a^2 + \rho^2)^{\frac{1}{2}} + a\right]\left[\left\{a^2 + (2l - \rho)^2\right\}^{\frac{1}{2}} + a\right](2l - \rho)^2}$$
$$= -W \log \frac{\left[(1 + y^2)^{\frac{1}{2}} + 1\right]\left[\left\{1 + (2x - y)^2\right\}^{\frac{1}{2}} - 1\right]y^2}{\left[(1 + y^2)^{\frac{1}{2}} - 1\right]\left[\left\{1 + (2x - y)^2\right\}^{\frac{1}{2}} + 1\right](2x - y)^2}$$
$$= 2Wx(x - y) \text{ approx.} \qquad (32)$$

where $l/a = x$ and $\rho/a = y$. Both x and y are less than unity and y is a small quantity where the heating is important. Let l_n be the depth of the nth cable in the duct and ρ_n the distance of its axis from the cable under consideration. For this latter cable the depth is l_0 and the distance ρ_0 is the radius of the sheath. If the principle of superposition be assumed as a first approximation then, provided the cables are equally loaded:

$$\theta_r' - \theta_m = \Sigma_0^n 2Wx_n(x_n - y_n)$$

and

$$\theta_m = 2W\Sigma_0^n \log\left[(2x_n - y_n)/y_n\right]$$

whence

$$\frac{\theta_r' - \theta_m}{\theta_m} = \frac{\Sigma x_n(x_n - y_n)}{\Sigma \log\left[(2x_n - y_n)/y_n\right]} \qquad (33)$$

θ_m is the actual temperature-rise at the mid point of the sheath and θ_r' the temperature-rise for a long duct.

If the cables are not equally loaded let:—

$$\theta_n = 2W_n \log\left[(2x_n - y_n)/y_n\right]$$

then,

$$\theta_m = \Sigma\theta_n$$

and

$$\frac{\theta_r' - \theta_m}{\theta_m} = \frac{\Sigma\theta_n x_n(x_n - y_n)/\log\left[(2x_n - y_n)/y_n\right]}{\Sigma\theta_n} \qquad (34)$$

θ_n is actually the temperature-rise produced at the sheath of the cable in question by the nth cable.

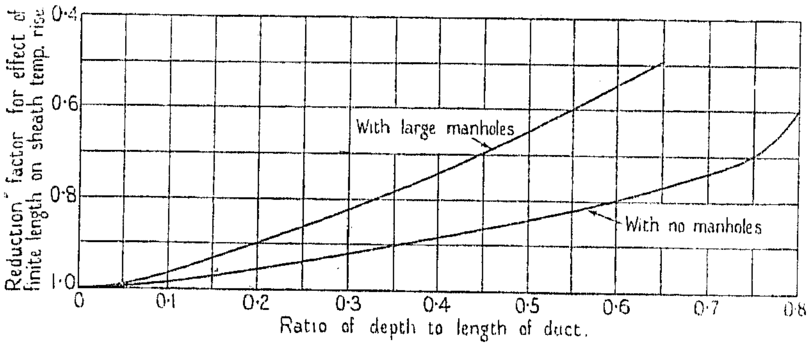


Fig. 34.—Reduction of sheath temperature due to finite length of duct.

Fig. 34 shows how the magnitude of the effect varies with the length of duct line in relation to its depth, being less than 5 per cent if the length is greater than 5 times the depth. For the Harlesden duct the effect is of the order of 1 per cent. The heating from portions of the cable run adjacent to the duct line have been neglected. In practice this approximation may often be made where such alleviation comes in question. If the cables continue, however, at the same depth then the effect of adjacent portions of the run may be allowed for by subtracting from θ_r', θ_m, θ_n, etc., the temperature-rise which would occur at the cable sheath in question if the duct had been absent and the adjacent conditions had been continuous throughout. Only the temperature-rise of the sheath has been considered. The relative alleviation of the core temperature is found approximately by multiplying the values given in equations (33) and (34) by the normal ratio of sheath to core temperature-rise.

(c) Effects due to dissipation of heat at ends of duct line.

If a duct line is terminated by manholes provided with ventilation or, as sometimes arises, filled with water, the end of the duct and of the surrounding soil, which forms a face of the manhole, will be cooled. As a simplified case it may be considered that the manhole surface is maintained at the ambient temperature. This is equivalent to maintaining a vertical plane, through soil and duct, at the end of the duct line and normal to it, at a fixed zero temperature-rise above ambient, since the temperature-rise is concentrated in or near the duct and conditions at a distance have only a slight effect.

This condition is fulfilled by adding a line "sink" (negative line source of heat) at each end of the cable and of the same length. At each end of these sinks are added line sources of equal length and so forth, giving a collinear series of sources and sinks. To each such source and sink is also added an image sink or source by reflection in the surface of the soil, so that the ground surface temperature is constant.

The mid-point temperature-rise θ_m due to the finite original duct and image is, from (32):

$$\theta_m = \theta_r' - 2W(x - y) \quad . \quad . \quad . \quad (35)$$

Now x and y are inversely proportional to a, so that the temperature-rise θ_m due to a cable 3 times the length and image is:

$$\theta_m = \theta_r' - (2/9)Wx(x - y)$$

Thus the temperature-rise due to the two additional cables at each end and their images is:

$$\begin{aligned}\Delta_1\theta_m &= 2Wx(x - y)\left\{1 - (1/3^2)\right\}\\ &= \left\{1 - (1/3^2)\right\}(\theta_r' - \theta_m) \quad . \quad (36)\end{aligned}$$

Similarly the temperature-rise due to the next two additional cables is:

$$\Delta_2\theta_m = (1/3^2 - 1/5^2)(\theta_r' - \theta_m), \text{ etc.} \quad . \quad . \quad (37)$$

But θ_r' corresponds to an infinite cable, whence:—

$$\theta_r' = \theta_m + \Delta_1\theta_m + \Delta_2\theta_m + \ldots$$

If ϕ_m is the temperature-rise with manholes, i.e. the temperature-rise due to the combination of sources and sinks:—

$$\phi_m = \theta_m - \Delta_1\theta_m + \Delta_2\theta_m - \Delta_3\theta_m + \ldots \quad (38)$$

Whence

$$\begin{aligned}\theta_r' - \phi_m &= 2(\Delta_1\theta_m + \Delta_3\theta_m + \ldots)\\ &= 2(\theta_r' - \theta_m)\left\{(1 - 1/3^2) + (1/5^2 - 1/7^2) + \ldots\right\}\\ &= 2{\cdot}26\,(\theta_r' - \theta_m)\end{aligned}$$

Thus if manholes normally at ambient temperature are present, the alleviation due to finite length of duct, which has been calculated in (6), is increased 2·3 times. The upper curve of Fig. 34 illustrates this.

A duct of length less than 10 times the depth may experience, if provided with manholes, an alleviation of 5 per cent of the sheath temperature-rise. This may correspond to an increase in rating up to about 2 per cent. Thus if an isolated duct is employed to carry a group of cables under a road it may be possible to allow a slight increase in the normal rating of the duct, but in general the alleviation is too small to be taken into account. For the Harlesden duct the upper limit of the error in sheath temperature-rise due to longitudinal conduction of this type is about 3·5 per cent. The experimental evidence, however, is that the actual figure is less and inappreciable compared with other causes of variation.

APPENDIX 3

Intermittent Rating

Let the temperature-rise of the core be θ and associated with a thermal capacity S per cm. in the cable. Let θ' be the temperature-rise of the sheath associated with a thermal capacity S_e in the earth. Let G_e be the thermal resistance per cm. from sheath to the earth's surface and G' the internal thermal resistance per cm. of the cable. A load I suddenly switched on gives rise to the following equations:—

$$\frac{d\theta}{dt} + \frac{\theta - \theta'}{SG'} = \frac{RI^2}{S}\rceil \quad . \quad . \quad . \quad . \quad (39)$$

$$\frac{d\theta'}{dt} + \frac{\theta'}{S_eG_e} = \frac{\theta - \theta'}{S_eG'}. \quad . \quad . \quad . \quad (40)$$

where R = resistance of cable per cm.
$\rceil$ = Heaviside's unit function.
t = time from switching on.

If $p = d/dt$—

$$p\theta + \frac{\theta - \theta'}{SG'} = \frac{RI^2}{S}\rceil \quad . \quad . \quad . \quad . \quad (39.1)$$

$$p\theta' + \frac{\theta'}{S_eG_e} = \frac{\theta - \theta'}{S_eG'}. \quad . \quad . \quad . \quad (40.1)$$

whence—

$$\theta = \frac{S_eG'p + (G' + G_e/G_e)}{SS_eG'p^2 + p\left\{(S/\lambda) + S_e\right\} + (1/G_e)}RI^2\rceil \quad (41)$$

but in nearly all cases S_e is much greater than S. Thus equation (41) reduces to—

$$\theta = \frac{S_eG'p + (G' + G_e)/G_e}{SS_eG'\left\{p + (1/SG')\right\}\left\{p + (1/S_eG_e)\right\}}RI^2\rceil \quad (42)$$

which in turn reduces to—

$$\theta = RI^2\left[G_e(1 - e^{-t/S_eG_e}) + G'(1 - e^{-t/SG'})\right] \quad (43)$$

but with greater accuracy we may substitute—

$$\theta' = G_ERI^2(1 - e^{-t/S_EG_E})$$

whence—

$$\theta - \theta' = G'RI^2(1 - e^{-t/SG'}) \quad . \quad . \quad . \quad (44)$$

But if I is αI_0, where I_0 is the continuous rating and if θ_c and θ_s are the maximum permissible core and sheath temperatures respectively:

$$\frac{\theta - \theta'}{\theta_c - \theta_s} = \alpha^2(1 - e^{-t/SG'}) \quad . \quad . \quad . \quad (45)$$

θ' may be calculated more exactly than in the foregoing. It will later be shown that—

$$\theta'/\theta'(\infty) = \beta, \text{ whence } \theta'/\theta_s = \alpha^2\beta \quad . \quad . \quad (46)$$

where β is a known function of t.

From equation (45)—

$$\theta - (\alpha^2\beta)\theta_s = \alpha^2(1 - e^{-t/SG'})(\theta_c - \theta_s) \quad . \quad (47)$$

but—

$$\theta_s/\theta_c = G_e/(G_e + G') = k$$

Thus—

$$\frac{\theta}{\theta_c} = \alpha^2\left\{(1 - e^{-t/SG'})(1 - k) + k\beta\right\} \quad . \quad (48)$$

The temperature-rise in the soil may be considered as due to a constant cylindrical source Q of heat buried therein. Such a source in an infinite medium has been shown by one of the authors* to give rise to a temperature θ_r at a distance r from the cable axis of:

$$\theta_r = \frac{Qg}{4\pi}\int_0^t e^{-(a^2+r^2)/4Du}(1/u)I_0(ar/2Du)du \quad . \quad (49)$$

where I_0 is a Bessel function of the first kind with imaginary argument, a = radius of cable. Whence:

$$\frac{4\pi\theta_r}{Qg} = \int_{(r^2+a^2)/4Dt}^{\infty}\frac{e^{-u}}{u}du + e^{-(a^2+r^2)/4Dt}\left[\frac{\gamma_1^2}{2^2}\left(\frac{1}{\gamma_2 t} + \frac{1}{\gamma_2^2}\right) + \frac{\gamma_1^4}{2^2 4^2}\left(\frac{1}{\gamma_2 t^3} + \frac{3}{\gamma_2^2 t^2} + \frac{3\cdot 2}{\gamma_2^3 t^3} + \frac{3!}{\gamma_2^4}\right) + \ldots\right]$$

$$= -Ei\left[-(r^2 + a^2)/4Dt\right]^{\dagger} + e^{-(a^2+r^2)/4Dt}\left[\frac{R_1^2}{2^2}\left(\frac{1}{\gamma_2 t} + \frac{1}{\gamma_2^2}\right) + \ldots\right] \quad . \quad (49.1)$$

where

$$\gamma_1 = ar/2D$$

$$\gamma_2^2 = (a^2 + r^2)/4D.$$

With a semi-infinite medium, e.g. the earth, if r' is the axial distance from the image of the cable in the earth's surface:

$$\frac{4\pi\theta_r}{Qg} = -Ei\left[-(r^2 + a^2)/4Dt\right] + Ei\left[-(r'^2 + a^2)/4Dt\right] + e^{-(a^2+r^2)/4Dt}\left[\frac{\gamma_1^2}{2^2}\left(\frac{1}{\gamma_2 t} + \frac{1}{\gamma_2^2}\right) + \ldots\right] - i^{-(a^2+r'^2)/4Dt}\left[\frac{\gamma_1'^2}{2^2}\left(\frac{1}{\gamma_1'^2} + \frac{1}{\gamma_2'^2}\right) + \ldots\right] \quad (50)$$

For the periods in which we are interested the last term is negligible, while for the sheath temperature, $r = a$ and $r' = 2l$, where l is the depth of the cable and is much greater than a.

$$\frac{4\pi\theta'}{Qg} = -Ei(-2x) + Ei(-h^2/Dt) + e^{-2x}\left[\frac{4x^2}{2^2}\left(\frac{1}{2x} + \frac{1}{4x^2}\right) + \ldots\right] \quad (51)$$

where $x = a^2/4Dt$. But since x is small

$$-Ei(-2x) = -0\cdot577 - \log 2x$$

and

$$\frac{4\pi\theta'}{Qg} = -0\cdot577 - \log 2x + Ei(-l^2/Dt) + e^{-2x}\left(\frac{1}{2^2} + \frac{3!}{2^2 4^2} + \ldots\right)$$

$$= -0\cdot577 - \log 2x + e^{-2x}\log 2 + Ei(-l^2/Dt)$$

$$= -0\cdot577 - \log x + Ei(-l^2/Dt) \quad . \quad . \quad (51.1)$$

to the second order in x

But the final temperature $\theta(\infty)$ is

$$\theta(\infty) = (Qg/4\pi)\log 4l^2/a^2 \quad . \quad . \quad . \quad (52)$$

Thus:

$$\frac{\theta'}{\theta'(\infty)} = \beta = \frac{-0\cdot577 - \log x + Ei(-l^2/Dt)}{\log(4h^2/a^2)} \quad (53)$$

APPENDIX 4

Current Ratings in Amperes

The following Tables are in substantial accord with the E.R.A. Tables of current ratings now in course of issue. For standard purposes the E.R.A. Tables, which specify the precise conditions of operation and factors for departure therefrom, should be consulted. The rating of a cable is essentially dependent on these conditions.

(a) CABLES LAID DIRECT IN THE GROUND

Ground Temperature = 15° C. Thermal Resistivity of Soil = 120 thermal ohm-cm.

Table 25.—SINGLE-CORE CABLES UP TO 20 KV

Nominal area of conductor, sq. in.	Cables up to 1·5 kV			Cables for 3, 6 and 10 kV. Three cables touching in trefoil formation. (Temperature-rise 55 deg. C.), A.C.	Cables for 20 kV. Three cables touching in trefoil formation. (Temperature-rise 50 deg. C.), A.C.
	Two and three cables touching. Unarmoured or armoured. (Temperature-rise 55 deg. C.), D.C.	Two cables touching. (Temperature-rise 55 deg. C.), A.C.	Three cables touching in trefoil formation. (Temperature-rise 55 deg. C.), A.C.		
0·007	63	63	54	—	—
0·01	74	74	63	—	—
0·0225	121	120	101	99	—
0·04	170	169	142	135	128
0·075	242	241	204	194	187
0·10	284	283	239	228	221
0·15	357	353	299	282	274
0·20	428	420	350	331	321
0·25	490	478	397	372	354
0·30	540	525	436	403	382
0·40	624	608	502	464	442
0·50	710	694	564	522	492
0·75	895	835	675	640	601
1·00	1 077	965	764	—	—
1·25	1 197	1 037	814	—	—
1·50	1 340	1 122	880	—	—

---

* See Bibliography, (27).

† The exponential integral function. See Jahnke and Emde's Tables for properties.

Table 26.—Twin, Concentric, and Multi-Core Cables, 3–20 kV

Type	Concentric*			Twin, belted						Three-core, belted								Three-core, screened				Three-core S.L.-type	
Temperature-rise, deg. C. . .	55			55		50	55		50	55		50	40	55		50	40	55	50	55	50	55	50
Voltage, kV	3	6	10	3	6	10	3	6	10	3†	6†	10†	20‡	3†	6†	10†	20‡	10†	20‡	10†	20‡	10†	20‡
Nominal area of conductor, sq. in.				Circular conductors			Shaped conductors			Circular conductors				Shaped conductors				Circular conductors		Shaped conductors		Circular conductors	
0·0225	103	102	101	103	102	96	105	102	97	88	88	84		90	88	88		93		94		97	
0·04	142	141	140	143	141	134	145	141	136	122	122	117	105	125	123	119	106	128	123	130	124	133	126
0·075	204	203	202	205	202	193	207	203	194	175	175	167	151	179	177	170	152	182	174	184	176	190	180
0·10	240	239	238	242	238	225	245	239	228	205	203	196	176	210	208	200	178	211	203	216	205	223	210
0·15	304	301	300	302	298	283	305	302	287	258	255	245	217	263	261	250	220	262	255	266	257	275	260
0·20	364	359	358	357	352	330	360	356	335	302	300	287	254	308	307	291	259	305	297	310	300	323	305
0·25	411	403	401	402	396	373	407	401	380	344	338	325	287	349	348	331	299	344	334	351	338	359	341
0·30	452	446	441	442	439	415	447	443	422	382	378	361	320	387	386	369	327	380	372	388	376	392	378
0·40	526	520	514	516	512	486	522	517	494	442	438	419		447	446	427		443		451		455	
0·50	600	587	580	583	576	545	589	583	555	487	482	462		492	491	471		485		494		497	

* Outer conductor earthed or not earthed.

† Centre point earthed or not earthed.

‡ Centre point earthed only.

Table 27.—Twin, Concentric, and Multi-Core Cables up to 1 kV (D.C. or A.C.)
Temperature-Rise = 55 deg. C.

Nominal area of conductor, sq. in.	Concentric		Twin, circular		Twin, shaped		Triple concentric		Three- and four-core	
	D.C.	A.C.	D.C.	A.C.	D.C.	A.C.	3-wire balanced load, D.C.	Three-phase A.C.	Circular, A.C.	Shaped, A.C.
0·007	50	50	55	55					47	
0·01	59	59	63	63					55	
0·0225	103	103	106	106	108	107	94	82	89	93
0·04	143	143	146	146	154	151	134	115	124	128
0·075	205	205	210	208	222	217	194	167	179	184
0·10	244	244	250	247	260	255	228	204	210	216
0·15	314	314	316	310	327	318	291	256	264	271
0·20	380	378	380	365	390	373	351	304	313	320
0·25	436	432	435	412	446	426	401	344	348	358
0·30	482	475	481	460	502	476	442	384	388	400
0·40	559	552	557	534	578	555	524	448	455	465
0·50	635	627	631	602	653	616	598	512	507	517
0·75	806	790	796	734	818	750	764	648	600	612
1·00	940	905	932	812	960	829	894	748	641	652

(b) CABLES IN UNDERGROUND DUCTS

Temperature of Ground = 15° C.

Table 28.—Single-Core Cables up to 20 kV Run in 3-Way Ducts

Nominal area of conductor, sq. in.	Wire-armoured, temperature-rise 55 deg. C.	Plain lead sheath. Temperature-rise 35 deg. C.			
	2 or 3 cables,* D.C.	2 or 3 cables,* D.C.	2 cables up to 1 kV,† A.C.	3 cables up to 1 kV,† A.C.	3 cables 3 to 20 kV,† A.C.
0·007	55	43	43	41	—
0·01	75	60	60	57	—
0·0225	105	82	82	77	79
0·04	144	116	115	107	109
0·075	210	175	169	152	160
0·10	240	207	199	178	181
0·15	302	246	239	222	223
0·20	359	292	278	257	260
0·25	408	330	311	287	291
0·30	453	366	340	315	319
0·40	532	430	392	363	362
0·50	601	486	432	401	397
0·75	756	610	508	465	462
1·00	893	737	567	503	—
1·25	1 005	817	595	532	—
1·50	1 115	902	618	553	—

* Flat or trefoil ducts.

† Trefoil ducts only.

Table 29.—Twin, Concentric, and Multi-Core Cables up to 1 kV (D.C. or A.C.) Run in Single-Way Ducts

Nominal area of conductor, sq. in.	Concentric (temperature-rise 55 deg. C.		Twin belted and non-belted (temperature-rise 55 deg. C.)		Triple concentric (temperature-rise 55 deg. C.)		Three- and four-core belted and non-belted (temperature-rise 55 deg. C.)
			Circular or shaped conductor				Circular or shaped conductors
	D. C.	A.C.	D.C.	A.C.	Three-wire balanced load, D.C.	Three-phase, A.C.	
0·007	43	43	45	45	42	35	—
0·01	54	54	52	52	50	42	47
0·0225	86	86	82	82	81	69	75
0·04	116	116	120	120	111	95	101
0·075	168	168	173	173	167	136	146
0·10	198	198	204	203	192	162	172
0·15	248	248	255	254	241	206	211
0·20	288	288	296	292	286	242	246
0·25	325	323	337	326	326	275	277
0·30	361	358	374	361	360	303	307
0·40	430	426	442	424	426	356	357
0·50	493	486	505	482	486	405	400
0·75	625	611	—	—	616	512	—
1·00	739	710	—	—	734	603	—

Table 30.—Twin, Concentric, and Multi-Core Cables, 3–20 kV (A.C.) Run in Single-Way Ducts

Type	Concentric*			Twin, belted			Three-core, belted				Three-core, screened		Three-core, S.L. type	
Temperature-rise, deg. C.	55			55		50	55		50	40	55	50	55	50
Voltage, kV	3	6	10	3	6	10	† 3	6	10	‡ 20	† 10	‡ 20	† 10	‡ 20
Nominal area of conductor, sq. in.				Circular or shaped conductors			Circular or shaped conductors				Circular or shaped conductors		Circular conductors	
0·0225	87	87	87	88	88	85	75	76	73	—	79	—	81	—
0·04	120	120	120	122	120	117	102	104	100	91	108	105	110	107
0·075	168	172	172	173	171	166	146	147	143	127	151	146	153	148
0·10	200	203	204	203	201	196	171	173	167	148	177	171	179	174
0·15	253	252	253	257	255	246	215	217	209	186	222	217	226	219
0·20	300	299	294	304	302	288	253	254	244	218	258	254	263	257
0·25	338	340	337	344	341	324	286	288	276	245	291	285	297	290
0·30	372	372	370	373	372	356	313	313	301	268	318	311	325	315
0·40	437	437	435	434	439	416	364	361	349	—	365	—	374	—
0·50	496	495	494	490	486	466	406	406	392	—	414	—	420	—

* Outer conductor earthed or not earthed.

† Centre point earthed or not earthed.

‡ Centre point earthed only.

(c) CABLES IN AIR

Ambient temperature = 25 deg. C.

The current ratings in Tables 31 to 33 are not finally agreed values but are given for the purpose of indication.

Table 31.—UNARMOURED (SERVED) SINGLE-CORE CABLES UP TO 20 kV.

Nominal area of conductor, sq. in.	Cables up to 1·5 kV (temperature-rise 45 deg. C.)				3 cables for 3, 6, and 10 kV (temperature-rise 45 deg. C.)		3 cables for 20 kV (temperture-rise 40 deg. C.)	
	2 or 3 cables, D.C.*	2 cables, A.C.	3 cables, A.C., flat	3 cables, A.C., trefoil	Flat	Trefoil	Flat	Trefoil
0·007	54	54	51	49	—	—	—	—
0·01	63	63	61	60	—	—	—	—
0·0225	108	108	101	97	106	103	—	—
0·04	161	148	142	136	149	144	147	141
0·075	230	219	208	200	215	208	209	207
0·10	275	262	250	241	259	249	249	240
0·15	356	344	328	317	338	326	320	310
0·20	428	413	385	374	402	387	379	367
0·25	497	480	447	430	461	443	433	420
0·30	560	543	505	482	513	496	479	466
0·40	681	660	637	578	637	595	600	553
0·50	796	753	716	665	713	681	657	633
0·75	1 033	935	861	842	857	861	793	801
1·00	1 223	1 070	958	962	—	—	—	—
1·25	1 418	1 180	1 032	1 062	—	—	—	—
1·5	1 597	1 267	1 095	1 154	—	—	—	—

* Served only or armoured and served.

Table 32.—TWIN, CONCENTRIC, AND MULTI-CORE ARMOURED CABLES FOR VOLTAGES UP TO 1 kV (D.C. OR A.C.).

Nominal area of conductor, sq. in.	Concentric (temperature-rise 45 deg. C.)		Twin (temperature-rise 45 deg. C.). Circular or shaped conductors		Triple concentric (temperature-rise 45 deg. C.)		Three- and four-core belted and non-belted (temperature-rise 45 deg. C.)
	D.C.	A.C.	D.C.	A.C.	D.C.	A.C.	Circular or shaped conductors
0·007	45	45	48	48	—	—	41
0·01	54	54	59	59	—	—	50
0·0225	86	86	93	93	86	74	80
0·04	124	124	132	132	122	107	113
0·075	186	186	193	193	180	157	167
0·01	224	224	231	230	216	187	200
0·15	289	289	296	294	278	240	258
0·20	352	350	366	353	332	290	308
0·25	405	402	421	406	383	334	351
0·30	457	453	470	456	436	380	393
0·40	547	542	561	545	524	455	469
0·50	635	629	645	619	602	522	537
0·75	830	812	839	773	778	674	656
1·00	1 002	963	1 021	898	945	810	739

Table 33.—TWIN, CONCENTRIC, AND MULTI-CORE ARMOURED CABLES FOR 3 TO 20 KV.

Type	Concentric*			Twin, belted			Three-core, belted				Three-core, screened		Three-core, S.L. type	
Temperature-rise, deg. C. ..	45			45		40	45		40	30	45	40	45	40
Voltage, kV	3	6	10	3	6	10	† 3	† 6	† 10	‡ 20	† 10	‡ 20	† 10	‡ 20
Nominal area of conductor, sq. in.				Circular or shaped conductors			Circular or shaped conductors				Circular or shaped conductors		Circular conductors	
0·0225	95	94	94	97	96	91	83	83	80	—	91	—	95	—
0·04	132	132	133	136	135	129	118	118	114	99	128	124	133	129
0·075	193	193	194	200	199	187	175	174	168	144	185	180	192	188
0·10	230	230	231	239	238	222	210	209	200	173	221	214	229	224
0·15	294	293	295	307	305	288	269	267	257	218	281	276	294	283
0·20	344	344	345	367	365	344	320	319	306	256	337	327	350	338
0·25	409	409	408	423	420	393	367	368	353	295	385	374	400	386
0·30	463	463	459	473	469	439	411	416	392	331	431	414	444	428
0·40	550	547	543	559	555	521	486	487	464	—	503	—	523	—
0·50	635	630	627	637	631	592	551	553	524	—	568	—	594	—

* Outer conductor earthed or not earthed. † Centre-point earthed or not earthed. ‡ Centre-point earthed only.

DISCUSSION BEFORE THE TRANSMISSION SECTION, 19TH JANUARY, 1938

Mr. J. R. Beard: The Bibliographies at the ends of these two papers show to what a large extent The Institution has been responsible through its *Journal* for making available information on the current rating of cables. It is therefore worth recalling The Institution's pioneer work in promoting organized research, particularly in this subject. This began about 1909, when our Wiring Rules Committee were able to enlist the help of the National Physical Laboratory and of the cable makers in an investigation on the heating of cables with current, the results of which were embodied in a paper by Messrs. Melsom and Booth* in 1911. This was the beginning of the work now carried further by Messrs. Booth, Hutchings, and Whitehead. At the conclusion of Messrs. Melsom and Booth's paper some preliminary results were given comparing a small cable laid under various conditions, including that of being buried in the ground, and the authors made the comment: "The question of the heating of buried cables is a most important one. It has been somewhat outside the scope of the present work, however. So far as the authors are aware no attempt has been made by the engineers responsible for large cable systems to determine the temperature-rises on cable as laid."

Many of us who still feel comparatively young can remember the extraordinary ignorance of supply engineers as to the ratings of millions of pounds' worth of cables which they utilized, and how long it took to tackle the problem systematically. Much of the credit for doing this is due to this country and particularly to The Institution, who before the War (in 1913) set up a Research Committee, one of the first actions of which was to appoint a Buried Cables Research Sub-Committee under the Chairmanship of Mr. Duddell and, on his death, of Mr. J. S. Highfield. A report by Messrs. Melsom and Booth on existing knowledge on the subject was prepared for the Sub-Committee and published in the *Journal* in 1914.*

The importance of research was emphasized by the War, and in July, 1915, the Government set aside £25 000 for the promotion of scientific and industrial research, from which a grant was made for The Institution; a portion of this was allocated to the Buried Cables Sub-Committee. During the following years work was done at the N.P.L. and under Prof. Marchant at Liverpool University, but naturally under difficulties. It was mainly concerned with cables themselves and with cables laid in air, in ducts, and on the solid system; and did not deal with the important growing problem of armoured high-voltage cables laid direct in the ground. This particular aspect was brought prominently forward in our North-Eastern Centre by Mr. Charles Vernier, the mains engineer of the Newcastle Electric Supply Co.: so much so that the Council adopted the unusual procedure of appointing a special North-East Coast Sub-Committee to work in parallel with the original Buried Cables Sub-Committee and to deal with this particular aspect. Mr. Vernier, as chairman, and Mr. Fawssett and I as representatives of the North-Eastern Centre, had with us on that Sub-Committee Mr. Melsom (who was then at the N.P.L.) and Messrs. Welbourn and J. F. Watson, representing the Cable Makers' Association. This Sub-Committee did a considerable amount of research both at the N.P.L. and at the test-room of the Newcastle Electric

---

* *Journal I.E.E.*, 1911, vol. 47, p. 711.

* *Journal I.E.E.*, 1914, vol. 52, p. 780.

Supply Co., but on the formation of the British Electrical and Allied Industries Research Association in 1920 its work and that of the Buried Cables Sub-Committee was transferred by The Institution to the new body, which dealt with the combined cable research through a committee under the chairmanship of Mr. Vernier. It was a great loss to cable research when he died some years later, but most of those who were associated with him in this early work, including Messsrs. Fawssett, Melsom, Booth, Welbourn, and myself, have for nearly 20 years continued to take an active interest in it. The earlier results were contained in the E.R.A. Reports published in the *Journal* in 1921 and 1923.* In the intervening 15 years much further work has been done, the latest results of which are given in the paper by Messrs. Whitehead and Hutchings.

I would call attention to four items of special interest in the paper of Messrs. Whitehead and Hutchings. They are: (1) Development of technique for measuring soil resistivity on site. (2) The depth rating factors for depths up to 18 ft. given in Table 5. (3) The group rating factors given in Figs. 13–16. (4) The effect of intermittent loading (Fig. 17).

The depth rating factor is of particular interest, as until this work was done many engineers were under the impression that the heating of a cable buried at 18 ft. would be cumulative and that such a cable would have practically no rating, whereas it will be seen that the rating is only reduced by 15 to 20 per cent on account of the depth of laying.

One very important result of these researches to the cable user is that it is now possible to put upon the cable maker who supplies and lays a complete feeder cable the responsibility for checking conditions during laying, for increasing the section where necessary, and for giving at the conclusion of the contract a guarantee of the specified carrying capacity. In other words, the user can now buy a complete feeder cable of definite capacity, just as one can purchase from an alternator manufacturer an alternator of a definite output.

Dr. Ezer Griffiths: Messrs. Whitehead and Hutchings refer to measurements which we have carried out of the thermal resistivity of soil by the "buried sphere" method. It may be of interest to amplify their account, as this is a subject to which we have devoted much attention. These activities had their origin in a discussion I had with Mr. Wedmore on the question of thermal-resistivity data.

Our first series of experiments were carried out with 4-in. diameter spheres, with thermo-elements distributed in the ground in the vicinity of the heated sphere and also some attached to the sphere surface. It was found that when the temperatures were plotted against reciprocals of the distances, measured from the centre of the spheres, the results would fall on a straight line as required by theory, except that the temperature of the shell was a little higher. This discontinuity in the vicinity of the sphere surface we believed to be due to a change in the properties of the soil in that region. We then carried out a further series of experiments using a 9-in. sphere and a different set-up of the apparatus.

Working with a large sphere it is possible to get the true resistivity of the soil by measuring temperatures at two points in the soil and not taking into account the temperature of the sphere surface. At the same time it must be remembered that the cable-layer is concerned not so much with the true resistivity as with the effective resistivity: hence the practice of taking the temperatures at the sphere and at a remote point.

I think the question of soil resistivity merits still further study to clear up some of the obscure effects observed. We have devised an apparatus for measuring the resistivity of soil under load. This is shown in Fig. A. It enables us to apply to the sample loads up to a ton or so per sq. ft., and to determine the effect of pressure on the volume and the resistivity.

The sphere method can also be used to obtain the thermal diffusivity of the soil. With an electrically heated sphere it is possible to vary the temperature of the sphere so that it follows approximately a sinusoidal curve. The spherical heat waves travelling outward from the sphere decrease in amplitude as the distance from the sphere increases. The amplitude and time-lag of the system of heat waves are measured at two points in the ground at a known distance apart. From measurements of these quantities two independent estimates of the diffusivity can be obtained. In practice it was found convenient to cause the temperature of the copper shell to follow a sine curve with a 6-day period.

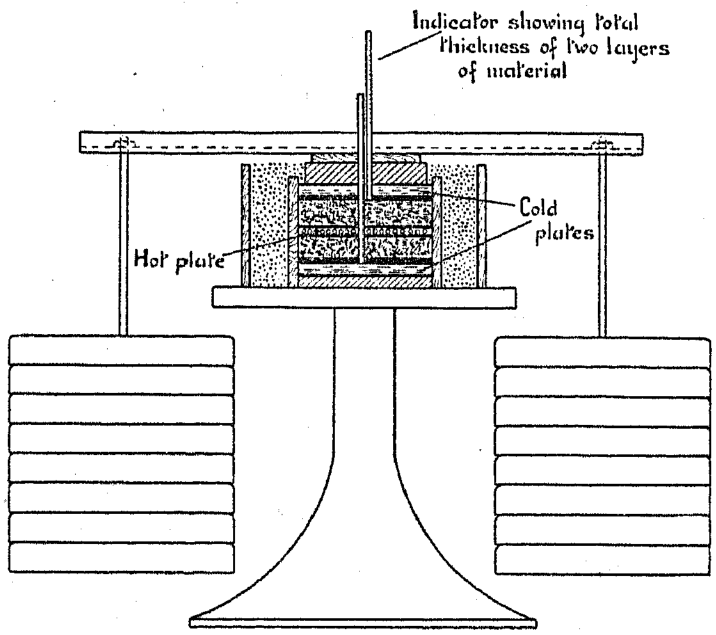


Fig. A

The theory of the method is as follows: The temperature of the surface of the sphere is given by the equation

$$\theta = \theta_1 + A_1 \sin \omega t$$

where θ_1 and A_1 are constants and $\omega = 2\pi/\text{period}$. The general solution of the differential equation for the heat flow for the above case is

$$\theta = \frac{Ae^{-\alpha r}}{r} \sin (\omega t - \alpha r) + \frac{r_1(\theta_1 - \theta_0)}{r} + \theta_0$$

where A is a constant, r_1 is the radius of the sphere, θ_1 is the (constant) mean temperature of the sphere surface, and

$$\alpha = \sqrt{\left(\frac{\omega}{2D}\right)}$$

---

* *Journal I.E.E.*, 1921, vol. 59, p 181; and 1923, vol. 61, p. 517.

D being the thermal diffusivity. By examination of the above expression it can be seen that the temperature at any point in the ground performs a sine wave of amplitude $Ae^{-\alpha r}/r$ about a mean temperature

$$r_1\frac{(\theta_1-\theta_0)}{r}+\theta_0$$

with a time-lag $\alpha r/\omega$ (reckoning from the centre, where $r = 0$). Hence from the experimental data two quantities—amplitude and the time-lag—can be obtained which permit of the calculation of the thermal diffusivity. The two methods of calculation are as follows:—

By ratio of amplitudes.—If the ratio of the amplitude at a distance a from the centre of the sphere to that at a distance b is m, then

$$\alpha=\sqrt{\left(\frac{\omega}{2D}\right)}=\frac{1}{b-a}\log_e\left(\frac{ma}{b}\right)$$

By time-lag.—If on the sine curves representing the temperatures at points distant a and b respectively from the centre the time-lag between corresponding readings is T, then

$$\alpha=\sqrt{\left(\frac{\omega}{2D}\right)}=\frac{\omega T}{(b-a)}$$

or

$$D=\frac{(b-a)^2}{2\omega T^2}$$

Mr. F. W. Purse: When they were preparing the Tenth Edition of the I.E.E. Wiring Regulations, the Wiring Regulations Committee of The Institution found that the tables of cable ratings given in the Ninth Edition required revision to bring them into line with modern conditions, and it was in that connection that the E.R.A. carried out a great many of the investigations which are recorded in these two papers.

It is difficult to apply always in practice the results, without deviation, which are set out in the papers. In certain cases, if we were to follow the authors' recommendations we should not be able to employ cables at all because, for example, the temperatures of hot flues through which cables have occasionally to pass must be almost up to the limiting value for cables. I also have particularly in mind certain cases which affect underground cables, where supply engineers are faced with the question whether it is better to switch off the supply or to run the cable beyond the temperature limit. We are told that in certain circumstances it is safe to run at 10 to 20 per cent above the current rating for an hour or two, and I should like to know what would happen if in cases of emergency we ran at, say, 40 per cent above the rating for half an hour, or some such other variations.

I suggest that the application of the authors' results would be made very much easier if the complete tables of cable ratings were given, and I hope that these will be included in the papers when they are published in the *Journal.**

Dr. E. H. Rayner: When considering the current densities at which small cables can be run I am reminded of a saying of Lord Kelvin some 80 years ago, that a man who is very thin will keep warmer if he has no clothes on; his clothes really act as a method of getting the heat out of him. It may therefore be possible to run a fine wire covered with insulating material at a higher current-density than if it had no covering at all.

As I have been in some degree responsible for the initiation and carrying-out of some of the work described in the papers, I hope that the information cannot fail to be of value to cable engineers. Definite information is now available on the heating of cables in normal use and in abnormal circumstances, which ought to enable economies to be made, aggregating in time a very large sum. The papers represent the results of work which could hardly have been carried out except on a co-operative basis, guided by representatives of the supply and manufacturing industry.

Attempts in the past to assess the carrying capacity of cables when on commercial loads have not afforded the steadiness of conditions necessary for satisfactory results; but it may be that, with the information now available, cable engineers may think it worth while to do some work on cables carrying commercial loads, and information of this kind, complementary to the work under laboratory conditions, could not fail to be useful.

The service required of cables and other electric plant is governed by experience. Above a certain load, depending in part on loading conditions, experience shows that failures may, in time, be encountered. Experience dictates the limits of operation, while the causes of the limits may be subjects of research, leading to modifications in design and use. Learning from failures is a most important basis of improvement; and I suggest for the consideration of the Transmission Section Committee that cable laying, maintenance, and usage, might form a subject for a valuable informal discussion and exchange of information.

I understand, for instance, that the experience of some cable engineers is that, if a certain minimum size of manhole is not available, trouble at bends, etc., may occur which would not be likely to happen if more generous provision were provided for bends, etc. Another subject might be the effect of short-circuits on transmission cables, due to thermal expansion or other causes. One knows that the core may lengthen very considerably under such conditions, and cause trouble at joints. On the other hand, when carrying out tests for the E.R.A. on a straight run of 500 ft. of 3-phase cable at the N.P.L. some years ago, we found that the lead covering kept the same length as the copper. The cable was not provided with the usual end fittings, and there were no sudden overloads. There was sufficient friction between the copper and the paper, and between the paper and the lead, for the copper to force the lead to expand equally. It would be of interest to learn how the results of sudden overloads affect cables of different types and sizes.

The papers are so full of details that cable engineers who have not been familiar with the course of the experiments involved can hardly have considered them at all critically and have endeavoured to see what light they may throw on their own experience. They are of a type which it might be useful to have in print 6 months before being discussed, in order that the correlation of engineering experience and research experiments might be more adequately dealt with.

---

* The Tables have now been included.

Dr. A. H. M. Arnold: Those who have changed over from d.c. to a.c. supply will be relieved to find that in the majority of cases they will not have to de-rate their cables. Most cables are of less than 0·5 sq. in. cross-section, and with these sizes almost no reduction in rating is required, except in those instances where the cables are far apart. Above 0·5 sq. in. the a.c. losses increase considerably faster than the d.c., but what is the advantage of using these large sizes of cable?

Messrs. Whitehead and Hutchings quote two formulae of mine for calculating the proximity losses in large cables, namely equations (2.2) and (2.3) in their paper. The first, for single-phase systems, is very simple; while the second, for 3-phase systems, is not quite so simple. I should, however, explain that there is no real difference between single-phase and 3-phase systems, and the two formulae must be equally complicated. Equation (2.2) was developed in the course of a research on single-conductor cables where, owing to the presence of the lead sheath, the cores were necessarily far apart. For such a condition the proximity effect can be taken as being proportional to the square of the separation between the cores, and a very simple formula is adequate; but, if the cores are brought very close together, as happens where the cores, single-phase or 3-phase, are contained in a single sheath, then the proximity effect is proportional to a much higher power than the square, so that that formula would underestimate the losses and a more complicated formula is necessary. Equation (2.3) is a more complicated formula for the 3-phase case, but there is a similar formula for single-phase cables which should also be used for twin-core.

The second of these formulae is misquoted by the authors. The point is a minor one, but in the denominator of that equation we have

$$\left[1 - \frac{5}{24}\frac{x^2y}{G(x_1)}\right]$$

and strictly speaking it should not be y but the equivalent of y for the factor x_1 instead of x. This makes a slight difference to the answer.*

Mr. T. N. Riley: The limiting temperature-rises stated in the paper are arbitrary figures, not determined by fear of electrical damage to the insulating material. They are mechanical limits rather than electrical ones. If those temperatures are exceeded, mechanical troubles may be set up through expansion and contraction of the sheathing and compound causing more or less permanent voids; and, particularly in duct sections, through expansion and contraction of the sheathing. Improvements in dielectric structure in the future may render a greater range of temperature safe and would result in increased ratings.

Mr. Purse asks what would happen to a cable if a serious overload persisted for some time, so that the temperature rose considerably above normal. Excluding, of course, fault currents, there would be no fear of immediate breakdown of the cable, since it would be (temporarily, at any rate) a full cable, and the thermal resistivity would be at its lowest level. Possibly when it reached cool conditions again its thermal resistivity would be higher than before, owing to the creation of voids in the dielectric. How far permanent damage would be done would depend on the type of cable and the normal operating voltage.

Arbitrary figures have been taken also for the thermal resistivity of the dielectric; for the lower-voltage cables this figure is 750 thermal ohms and for the high-voltage cables it is 550. These values are based on practical experience as to the homogeneity of structure which it is possible to secure during manufacture and maintain in service for the different insulation thicknesses. Expansion and contraction of compound, creating voids, also causes increased thermal resistivity, though as the voids fill up again at the higher loads this effect is not so important unless there is permanent longitudinal displacement, as sometimes occurs. If special impregnating means are employed to avoid the creation of voids, as in the case of cables of 33 kV and over, it is quite practicable to come down to a value of the order of 400 thermal ohms.

With regard to the thermal resistivity of the ground, many soils which may differ appreciably in structure are frequently classified under one head, and caution should be exercised in using tabulated values of thermal resistivity. The term "clay" may include, for instance, soils of a wide range of thermal resistivity. London clay is totally different from Newcastle clay, which has the lowest thermal resistivity of any soil in this country, apart from solid rock. It is particularly highly compacted, probably as the result of the superimposed ice load when covered by a glacier in earlier ages.

The depth-correction factors quoted in the paper refer to homogeneous soils. In very many localities the characteristics of the soil vary with the depth. Sometimes, for instance, there will be surface layers of made ground of high resistivity down to 4–5 ft., with clay below. As the clay is approached, the thermal resistance begins to drop, instead of continuing to increase with depth. A minimum value is reached a short distance into the clay and then, deeper down, the ordinary depth-correction applies again. Where there is clay over chalk, as in some of the London areas, the reverse effect may be displayed and the thermal resistance may increase more rapidly than the depth-correction factor indicates. It is necessary to take a thermal-resistivity measurement at the depth at which the cables are to be laid; it is not satisfactory to take the figure at another depth and assume that it can be used with a correction factor to indicate the conditions at other levels.

Fig. 6 of the paper by Messrs. Whitehead and Hutchings shows the reduction in internal thermal resistance due to the use of shaped conductors. On the other hand, when the diameter of the cable is smaller the external thermal resistivity is increased. With higher-voltage cables these effects nearly balance, and there is astonishingly little difference in the currents which the cables will carry. The shaped conductors have only slightly higher ratings.

With regard to the duct system of cable-laying, it is interesting to note the marked effect of eccentricity of the cable in the duct. Of the three ways in which the heat is disposed of between the cable and the duct, namely convection, conduction, and radiation, two change relatively little with change of position in the duct, but conduction changes very greatly. If the cable is " snaked " in the duct, so that it stands away from the floor, there may be an appreciably higher temperature-rise locally at that point than at other points where it is in contact with the face of the duct.

---

* The formula has since been corrected.

Mr. H. W. Baxter: The paper by Messrs. Whitehead and Hutchings deals with the emergency rating of paper-insulated cables but gives no similar data for vulcanized-rubber cables in buildings. This emergency rating is clearly of some importance, as the I.E.E. Wiring Regulations (Tenth Edition) permit a temperature of 140° F. for relatively long periods, although 120° F. is the recognized working temperature.

These cables are frequently protected by fuses, and ideally the performance of the fuse should be properly matched to the cable characteristic if damage to the insulation on overload is to be prevented. This cable characteristic can be determined from the heating curve, providing the maximum permissible temperature-rise is known. For example, Fig. B shows a family of heating curves for a vulcanized-rubber cable which, when loaded continuously at 15 amperes, attains the recognized temperature-rise of 20 deg. F. On 25 per cent overload this temperature-rise is attained in $3\frac{1}{2}$ minutes (Point Q). Hence the fuse should blow in $3\frac{1}{2}$ minutes on 25 per cent overload if this temperature-rise is not to be exceeded. The procedure is similar for other overloads. At 50 per cent overload the corresponding time (Point P) is $2\frac{1}{2}$ minutes, and so on. Replotting these points gives the cable characteristic shown in Fig. C, Curve P.

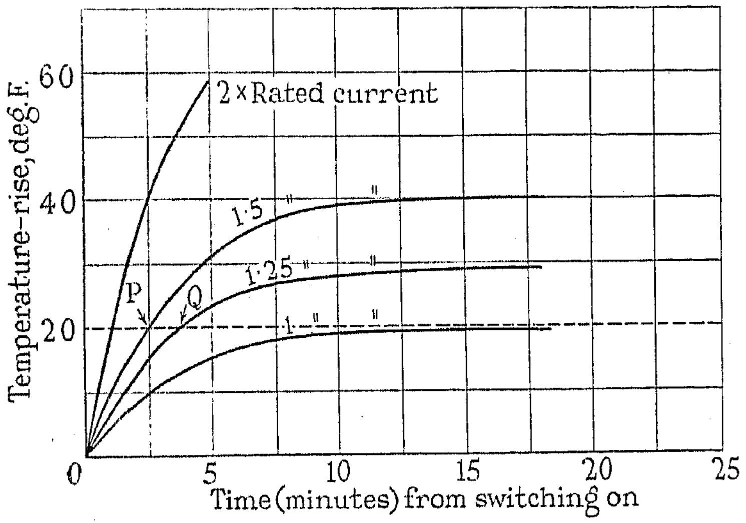


Fig. B.—Heating curve for 15-ampere vulcanized-rubber cable. Rated current $I = 15$ amperes.

It is recognized that under emergency loading conditions this 20 deg. F. rise may be exceeded. Curve R of Fig. C assumes a tolerance of 10 deg. F. on the heating of the cable, corresponding to a maximum rise of 30 deg. F. under overload conditions. The Wiring Regulations imply a tolerance of 20 deg. F., and if this could be reduced (this would imply more precise fusing) the cable rating could be increased and a corresponding saving on the cost of an installation would result.

These cable characteristics are based on the assumption that the temperature of the cable should not exceed a predetermined figure, but I should be interested to know to what extent this could be modified in practice. We can run a cable at 120° F. (20 deg. F. rise) indefinitely, and the Wiring Regulations permit 140° F. for 4 or 5 years. Could not even higher temperatures be tolerated for shorter times? It would be useful to know just how hot one could run a cable for, say, 1 second, 1 minute, and 1 hour, without damaging the insulation. If this information were available it should be possible to draw a curve such as Q in Fig. C. This is based on a rise of 20 deg. F. on sustained rated load, and assumes that for short periods this rise may be exceeded, the permissible temperature increasing as the time is reduced. On this basis the emergency rating of the cable would be somewhat higher than the values suggested by the authors, more especially for the shorter-period loadings.

Mr. W. H. Lythgoe: I strongly support Mr. Purse's plea that when the papers are finally printed in the *Journal* they be accompanied by the complete tables of cable ratings.

I should like to make one or two observations on the paper by Messrs. Whitehead and Hutchings. On page 519 the theory of skin and proximity effects is worked out for circular-conductor cable, and I should like to ask the authors whether they know how the theory differs for shaped-conductor cable. The shaped-conductor multi-core cable is at the present time, and will probably be in future, of far greater importance than the corresponding circular-conductor cable.

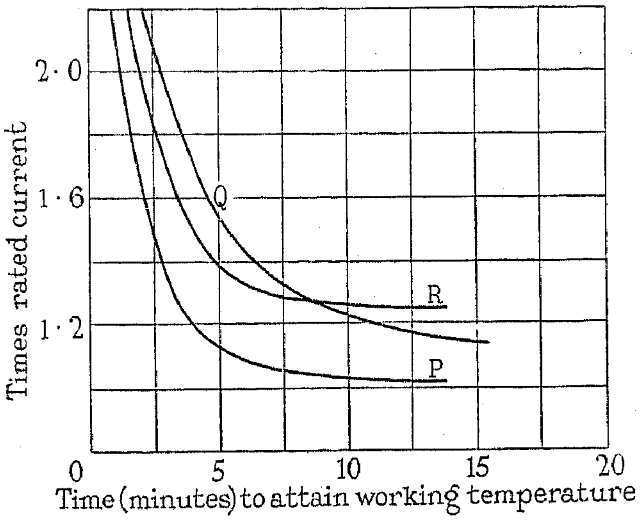


Fig. C.—Characteristics of 15-ampere vulcanized-rubber cable.

Curve P. Temperature-rise 20 deg. F.
Curve Q. Temperature-rise 20 deg. F. on sustained rated load, with higher temperature-rises for short periods.
Curve R. Temperature-rise 30 deg. F.

Despite the negative results so far obtained by the authors as regards a progressive and consistent decrease of soil thermal-resistivity with depth, there seems to be some supporting evidence for such an assumption. It is possible that further work may justify defining the soil thermal-resistivity as that obtained at the surface, i.e. uncompacted, and to adopt a simple correction curve for various depths of laying. Also, for practical purposes, to adopt two basic values of soil thermal-resistivity, based on coarse- and fine-grained soils respectively.

Equation (8.1) on page 526 seems misleading; I infer that the factor G_e is the additional apparent thermal resistance due to the heating derived from the associated cables, and the total thermal resistance of the cable under the conditions contemplated should be the summation of equation (8.1) on page 526 and the similarly-numbered equation on page 527.

With regard to the factor k mentioned on page 527, the value of 0·66 for S.L. cables appears to be somewhat low. Results which we have obtained suggest a figure more of the order of 0·85.

On page 528 it is stated that in assessing the intermittent rating of the cable the thermal capacity is assumed to be that of the conductors plus half that of the insulation; it would be interesting to have more information as to the basis of this assumption.

In Table 8, useful data are given regarding the emissivities of various types of sheathing under different conditions, but possibly a more definite lead could be given by the authors as to the values normally to be assumed. Suitable values, judging by an inspection of these results, would appear to be 0·5 for lead sheaths and 1·0 for duct materials.

It would be helpful if a list of symbols could be included when the paper is printed in the *Journal*;* at present the same symbol is used for more than one quantity.

Mr. A. H. Bennett: I am particularly interested in the authors' description of the sphere method of arriving at the thermal resistivity of the earth. As practical users of cables we may be laying a cable 5–6 miles long through a valley largely composed of clay and similar soils, and continuing 5 or 6 miles over a range of hills consisting partly of chalk and partly of sand. By carefully studying the paper of Messrs. Whitehead and Hutchings we shall be able to decide whether to increase the size of the cable. To take an illustration, if we are contemplating using a 33-kV cable with 0·2-sq. in. conductors we may find it advisable to increase the size to 0·25 sq. in.

Perhaps the authors of this paper could tell us a little more about the temperature of the soil at the time of maximum demand. Assuming in the first place that the heavy-loading period of the cable occurs in the winter, when the earth resistivity is likely to be good, what is the factor which will give the rating if the cable is to be used with a maximum load in the summer?

With regard to the question of the maximum safe loading of cables, during the late war 3-core 11-kV cables of 0·1-sq. in. section were carrying loads up to 250 amperes, not for a few minutes but for hours at a time. Probably a minimum load of 100 amperes was carried for nearly 24 hours per day, excluding meal-times, when the factories were half shut down. We must have been getting close to the danger limit with those cables, and I should like to know how close to it we did get.

It is sometimes suggested that voltage-drop, and not temperature, is the real controlling factor in the problem of current rating, but I am inclined to disagree on this point. In these days of regulators at the ends of high-voltage feeders we are not very worried by a 5 or 10 per cent drop, because we have the means of picking it up, if it is economically worth while to do so, for a short period; but if we do so we may be running into a very dangerous situation from the temperature-gradient point of view.

Mr. S. W. Melsom: Those who, like myself, were concerned with these questions in the early days had a great advantage over those who were to follow. It is not to be expected that the work of later investigators can show so great a saving in cost as did the early experiments. Nevertheless, the large increase in the size of installations and the introduction of different methods of laying cables have produced a group of problems which have required full investigation, and the production of current-rating figures appropriate to the newer conditions.

To my mind the most important features of the papers are:—

(1) The completion of the general formulae by means of which ratings for almost any size of cable, run in almost any way, can be accurately calculated. These formulae have been built up step by step as more complete knowledge has been gained as to the physical constants involved.

(2) The investigation of the problems that have arisen from time to time in connection with the supply of large alternating currents in steel-framework buildings and in ships. Until the E.R.A. investigated the matter, knowledge of this subject was vague and unsatisfactory. It is now on a proper footing, however, and it is pleasing to note that as a result of the investigation it has been possible to formulate comparatively simple rules, mainly by allowing a suitable spacing between the cables and the steel or ferro-concrete wall, although in the case of very large cables special precautions have to be taken.

(3) The rating of cables in ducts. Here again, until the E.R.A. work was carried out the knowledge of the subject was, to say the least of it, incomplete, the best information available being the old V.D.E. rule that the rating of cables grouped in the duct should be reduced to 75 % of the value for a single cable.

It has been known for some time that plain lead-sheathed cables laid in ducts give more trouble than armoured cables laid direct in the ground, and the reason generally put forward for this has been that the cable was free to expand within the duct and was subjected to mechanical damage due to the movements with expansion and contraction. Consideration of the conditions under which many cables in ducts are operated according to the figures put forward by the authors show that these cables have often been operated at a much higher temperature than the normal limit, and therefore that the mechanical forces set up by expansion and contraction have been very much larger than they would have been had the E.R.A. figures been available.

It is to be hoped that Section (4) of the paper by Messrs. Whitehead and Hutchings will receive the closest attention of those operating cables in duct lines.

I should just like to say a word or two on the important question of the basis of the temperature ratings. It is well known that the E.R.A. figures are calculated on the basis of definite temperature limitations which are either settled by The Institution or arrived at as a result of discussion round the committee table of the E.R.A. The idea used to be current that the maximum temperature for operation was that at which the dielectric was not adversely affected by the high temperature; full consideration by all the interests concerned has shown, however, that there is no place at which a sharp line can be drawn, but that many factors have to be taken into consideration.

---

* This has now been added.

There are, for instance, such factors as the ambient temperature, the effect of the temperature both on the cables, and on the structure to which they may be attached, or on the hand which may touch them, and the mechanical forces set up by expansion and contraction due to the temperature-rise. Also there is the important question of voltage drop, a severely practical question that itself limits the current which may be passed through a cable in service.

An early instance of the importance of this subject was forthcoming when Mr. Booth and I produced our first sets of results, which showed that the current density of very small cables might be very high, when bounded by limits of temperature-rise. This is due, of course, to the curious and now well-known phenomenon that in these small cables the insulation acts as a conductor of heat rather than as a resistor, and that in consequence on the basis of temperature-rise alone some of the small cables could be rated to approximately 10 000 amperes per sq. in. As investigators we felt that this was of the utmost importance, but the Wiring Rules Committee of that day pointed out firmly, and quite properly, that under such conditions the voltage drop would be excessive and that the ratings would be impracticable. Although the calculated figures for a definite temperature elevation can be stated to a high degree of accuracy, the fact remains that the basis of rating is largely empirical.

The paper by Messrs. Whitehead and Hutchings shows how by attention to detail it may be possible to operate cables at somewhat higher currents than the values given in the appropriate tables, but the extent to which these comparatively small improvements can be applied in practice is and must be a matter of economics. For instance, if a close watch were kept on the thermal resistivity of the soil of any particular cable run, throughout the year, it might be possible to operate the cables at somewhat higher currents than those shown, but it is at least likely that the cost of the continuous watch on the thermal resistivity of the soil would be higher than that of slightly increasing the size of the cable and taking a proper factor of safety.

Mr. E. A. Beavis (*communicated*): With regard to the actual use of the formulae, there are one or two points to which I should like to refer. When considering the question of thermal capacity of the cable no mention is made of the lead sheath or cable coverings. Are these to be considered as negligible, and, if so, what is the position as regards the type of cable known as "S.L.," i.e. triple lead sheaths under one armouring?

The thermal capacity of the earth, S_e, is referred to, but no data are given as to its magnitude or calculation; although the use of this can be avoided, I think it would be advisable to insert values if these are available.

I realize that these points are only of minor importance and do not affect the calculations to any appreciable extent, but I think some references to them would help to clarify matters somewhat.

With reference to eddy-current losses in multi-core cables, we have made many practical measurements in the past and find that the results agree reasonably well with values calculated from the given formulae for the normal run of armoured cables. However, there are certain conditions in regard to steel-tape armour that need to be noted. This armour consists of two layers of steel-tape breaking joint, i.e. each is laid on the cable in a close helix with a small gap, the top layer covering the gap in the first layer below it. If the steel-armour resistance is calculated, considering it as a steel tube of the double thickness per cm. length, i.e. from the area at the mean diameter and a given resistivity, then the eddy-loss results appear to be correct. This value, however, is not the true resistance as given by measurements taken on the length of cable armour; the latter is given more nearly by taking the length, width, and thickness, and considering the two tapes in parallel. In the first case the resistance as calculated from the area decreases with increasing diameter, whereas in the second case it increases, for a given width of tape. Thus if the true measured values are inserted in formula (15), Appendix 1, the loss becomes entirely negligible for large cables, and this point should be noted. One or two of the actual measurements and calculations are shown here for comparison:—

Resistance of Double-Steel-Tape Armour

Tape	Outer diameter	Measured resistance per 1 000 yards	Calculated resistance	
			From length	From area
	in.	ohms	ohms	ohms
1 in. width, 30 mils	0·9	6·762	7·691	1·244
	1·26	6·824	10·88	0·888
2 in. width, 60 mils	3·01	2·825	3·34	0·186
	3·53	3·575	3·90	0·159
1½ in. width, 40 mils	2·18	5·466	6·665	0·385

There appears to be very good contact between the two tapes, and measured results are approximately identical in whatever way the bridge contacts are made.

With regard to the hysteresis formula (20.2) for the steel-tape armour, the thickness δ is that for the double tape.

Mr. H. C. Booth, Mr. E. E. Hutchings, and **Dr. S. Whitehead** (*in reply*): To Mr. Melsom's remarks regarding alternating-current ratings for cables in steel-framework buildings and in ships, it might be added that while data have been obtained for the Institution Wiring Regulations which relate to specific methods of installation, a mathematical solution has been found possible for the general case of proximity to steelwork, and this applies not only to cable installations but also to such problems as busbars and heavy-current connections in steel cubicles. Mr. Melsom also refers to the troubles experienced with plain lead-sheathed cables in ducts. While there is evidence that this has occurred even at light loads, a contributory factor lies in the non-provision of proper facilities for expansion and contraction of the cable, and where such facilities have been adequate the trouble is undoubtedly due to excessive temperature-rise. With regard to the high permissible current density in small cables, to which he also refers, the same reason to which he attributes this effect results in an increase in the current rating of cables in air with increase in working voltage. The question of operating buried cables at higher currents than those given in the tables is not so much a question of keeping a continuous watch on the thermal resistivity of the soil as of knowing beforehand the approximate maximum thermal resistivity of the type of soil for the particular cable run and making the appropriate rating correction to the tables on this basis.

We are indebted to Mr. Beard for his very interesting survey of the pioneer work on the current rating of cables and for tracing its development, as regards buried cables, to the investigations covered by the present papers. Arising from his remarks on depth rating factor it should be noted that, while in general there is a slight reduction in rating with increase in depth, soils seem to differ in this respect, and a greater depth of laying up to a certain limit, may even be advantageous. With regard to guaranteeing the carrying capacity of the laid feeder, proper emphasis should be put on the seasonal variation with certain types of soil, and any guaranteed rating should be based on the maximum thermal resistivity occurring during the year.

The E.R.A. has had the benefit of the close co-operation of Dr. Griffiths in its work on thermal properties of soils. He has been very ready to acknowledge the practical importance of the methods of measurement recommended in the paper as compared with those in which the thermal resistivity was calculated from temperatures measured entirely outside the source of heat. The latter results undoubtedly correspond more closely to the true physical properties of the undisturbed soil. The desirability of further study is recognized, and in fact an extensive investigation of a number of typical soils is already in progress. Since research on soils has now resulted in a scientific classification, it is hoped that the results of the work in hand will be on a more absolute basis than hitherto. Dr. Griffiths's description of apparatus for measuring thermal resistivity of soil under pressure is interesting, but in practice the properties probably depend not only on the static pressure but also on the previous history of the soil, as, for example, compacting under glacial pressure. The sinusoidally-varying-load method of measuring thermal diffusivity is accurate but somewhat complicated, and the results may not correspond to stable conditions if drying-out occurs. A simple but promising method now being investigated depends on plotting the initial heating curve for a buried heater. The curve of θ/Wg against Dt is characteristic only of the heater, where g is the thermal resistivity, D the diffusivity, θ the temperature-rise at the time t, and W the watt loading, so that if this characteristic curve can be deduced by calibration in a medium of known g and D, other media can easily be measured. Such a test can be carried out in a few hours only, and further work is being done to develop the apparatus.

The practice referred to by Mr. Purse of installing cables in hot flues emphasizes the importance of making adequate provision for cable-runs when designing buildings; this does not seem to be sufficiently appreciated by architects, who only too often assume that the cables can be installed in any duct or chase which may have to be provided for other services. The deterioration of the insulation due to high ambient temperatures may not be immediately apparent but must result in an unduly short life for the cables. The question of short-time overloads raised by Mr. Purse has been answered by Mr. Riley in his remarks. The formulae given permit the calculation of intermittent or transient loadings of any common type. The example he quotes would not result in any serious overload.

Dr. Rayner's remarks on current density in small cables have been covered by the reply to Mr. Melsom. He suggests also that information on cable failures under operating conditions and on the effect of short-circuits on cables should be collected. Both these subjects are already under investigation by the E.R.A.

In reply to Dr. Arnold, multi-core cables larger than 0·5 sq. in. are rarely employed, and in fact are not specified in B.S.S. 480 except for 1 kV where considerations of space, and auxiliaries such as terminal boxes and joints, may render a single cable desirable for short lengths. Larger single-core cables are occasionally used for the same reason. The proximity effect is then not so important; the skin effect and sheath losses are high but may be offset by savings in space and cost when short connections between stations and plant are involved. We would thank Dr. Arnold for his remarks regarding the formulae for proximity loss, and we agree that there is no real difference between the formulae for single-phase and 3-phase systems. This point has now been made clear in the paper; the approximate formulae are, however, satisfactory for rating calculations. The error in the second formula was a clerical one and has now been corrected.

While agreeing with Mr. Riley that permissible temperature-rise is limited by mechanical rather than electrical considerations, we would qualify this as regards rubber-insulated cables, where deterioration of the insulation occurs at comparatively low temperatures. His remarks on the variation of thermal resistivity under operating conditions are very interesting. The question of classifying soils is admittedly a difficult one, but it is hoped that the survey now being made, as previously mentioned, will help considerably in this direction. With regard to non-homogeneous soils, a theory has been worked out for two-layer soils. In some cases (shallow surface layers) the two layers may correspond to the "drift" and "solid" geology respectively, and the problem is then similar to that of the electrical resistivity of the earth. The theory is, however, difficult to apply in a general manner owing to local variations. The rating tables confirm Mr. Riley's opinion that there is no advantage in employing shaped-conductor cables in ducts or in air. "Snaking" of cables in ducts does theoretically result in higher temperatures locally, and theory has been confirmed by the tests, but it is probable that the effect will be in part reduced by longitudinal conduction.

In reply to Mr. Baxter, rubber-insulated cables are outside the scope of the E.R.A. tables. Actually, however, for these cables the formulae for the emergency rating of paper-insulated cables may be used, and data on this subject are given in the earlier paper by Melsom and Booth.* It is unfortunate that no accurate data are available as to the maximum temperature which a cable will sustain for very short periods without deterioration.

---

* *Journal I.E.E.*, 1923, vol. 61, p. 363.

The question of the limits which govern overloads of longer duration has been dealt with by Mr. Riley.

The effect of skin and proximity effects in shaped-conductor cables, referred to by Mr. Lythgoe, should not differ greatly from those in the corresponding circular-conductor cables, as the closer mean spacing in the former is partly offset by the greater circumferential distribution of copper. For buried cables it is possible to use a correction factor for the rating according to depth, and this has been given in the paper, but, as mentioned earlier, this assumes a homogeneous soil. The possibility of using two basic values for soil resistivity may also be considered, but more light may be thrown on this when the results of the fuller investigations now proceeding are available. With regard to equation (8.1) the factor given on page 527 does in fact represent the total thermal resistance of the cable when it forms one of a group. The term for $n = 1$ gives the thermal resistance arising from the flow of heat from the cable itself, while the terms for $n > 1$ give the influence effects of neighbouring cables. The ratio of sheath to core temperature, k, suggested by Mr. Lythgoe, appears rather high; in the numerous tests on which the present papers are based the values for 10- and 20-kV cables ranged between 0·6 and 0·7. Emissivities of different materials may be found from Table 8; 0·6 may be assumed as an average figure for plain lead cables in air or in ducts and for armouring "left bright"; 1·0 for served cables and for normal duct materials. A list of symbols is now included in the paper, as suggested by Mr. Lythgoe.

As shown in the Appendix, the thermal capacity of a buried cable is effectively distributed across its internal thermal resistance so that half the thermal capacity of the dielectric may be considered as connected across the whole of its thermal resistance, except for unusually large sizes. For cables in air this is not true, and a greater fraction should be used for small cables. Actual tests, however, showed that the previous approximation was substantially valid for large sizes and it has therefore been retained for uniformity. The effect of type of construction and mode of installation makes it necessary to take a conservative general figure.

Mr. Bennett asks for information on soil temperature at the time of maximum demand. Naturally where a feeder serves an industrial load this may occur even in the middle of summer, when the soil temperature in this country at normal depths is of the order of 15 to 20° C. The reduction factor for summer loading if this has not been allowed for would vary according to the type of soil; for heavy soils it would be not less than 0·9, but for light sandy soils it might be as low as 0·7. The example of overload quoted by Mr. Bennett is not so serious as might be anticipated; although the continuous rating for the cable in question is 196 amperes, the core temperature when carrying an intermittent load of 250 amperes would only be 79° C. instead of the 65° C. permitted. The limitation imposed on rating by actual voltage-drop applies only to small cables installed in buildings. In public supply it is the diversity of the voltage-drop which is the important factor.

Several speakers have urged the inclusion of the rating tables in the paper; these have now been added.

In reply to Mr. Beavis, the thermal capacity of the lead sheath or cable coverings has been taken into account in computing the transient current ratings of cables in air, and the definition of S has now been amended accordingly, following substantially the method given by Melsom and Booth. For cables laid direct, the thermal capacity of the sheath and coverings is included in the capacity of the cable or in the capacity of the earth, according to the value of the equivalent diameter of the cable used in computing β. To avoid undue labour the equivalent diameters have been approximated in such a way as to require as few different values of β as possible. Thus in a strict sense the thermal capacity of the sheath, etc., should sometimes be included and sometimes neglected, but since it has little effect to the degree of approximation attempted the same definition of S may be used throughout. In the portion of the analysis where the symbol S_e is used, the thermal capacity of the earth to which it refers may be taken as much greater than that of the cable, so that this factor is thereby eliminated. Where it is necessary to take the thermal capacity of the earth into account, it is introduced by means of the quantity β, since in such circumstances it would be necessary to make S_e a function of time and the symbol would become inconvenient. The quantity S_e is, therefore, not used directly and no value need be given. The nature of the thermal capacity of the earth is analysed in some detail in Appendix 3. The information on steel-tape-armoured cables is very interesting. The E.R.A. has work in hand on this subject, but it is not complete, and we have to content ourselves with the practical approximation of taking the ratings as being the same for steel-tape and wire armour. Nevertheless, it is hoped later to give more exact indications of the behaviour of tape-armoured cables. The observations of Mr. Beavis agree with our preliminary results and will be of considerable value in pursuing the studies in hand.

ROTATIONAL HYSTERESIS LOSS IN ELECTRICAL SHEET STEELS*

By F. BRAILSFORD, Wh.Sc., B.Sc.(Eng.), Associate Member.

(*Paper first received* 31*st January, and in final form* 17*th March*, 1938.)

SUMMARY

The paper describes how rotational hysteresis loss in small disc samples of sheet steel may be measured in a simple manner by a new method, the loss being determined directly without the inclusion of eddy-current losses. The difficulty in the way of making measurements on a single disc, due to the magnetic anisotropy of the material, is indicated. The magnetic anisotropy in commercial electrical sheet materials is then briefly discussed, and it is shown how by use of a sample made up of three similar discs the experimental difficulty may be overcome.

The observed results on four electrical sheet materials are then given.

The loss, plotted against flux density, is seen to fall rapidly towards zero near saturation, as has been found for various ferromagnetics by other investigators, but a sharp increase in loss, hitherto unreported, is shown to occur, for all four materials, at a point near the " knee " of the magnetization curve. A qualitative explanation of this phenomenon and of the general form of the loss curve is given on the basis of the " domain " theory of ferromagnetism.

INTRODUCTION

The hysteresis loss occurring in sheet iron and steel subjected to an applied field rotating in the plane of the sheet was first determined by Baily.† Later, other workers investigated rotational hysteresis losses in ferromagnetic materials, notably Beattie‡ for nickel and cobalt, Weiss and Planer§ for steel, and Seiyama‖ for iron and nickel. The methods employed led to appreciable eddy-current losses in the sample, for the separation of which from the total iron loss measured some suitable expedient had to be adopted.

The iron losses occurring in the magnetic circuits of rotating electrical machines result from a combination of rotational and alternating effects, and an accurate knowledge of the rotational hysteresis loss in the magnetic materials involved is therefore desirable. Moreover, it is known that the general relation between the rotational hysteresis loss and the magnetization is a peculiar one and quite unlike the corresponding relation in the case of alternating hysteresis loss. Hence an accurate knowledge of this relation should contribute to an understanding of the mechanism of hysteresis loss in ferromagnetics generally.

In the present investigation the rotational hysteresis loss has been measured by a simple and direct method on disc samples, and uncertainty due to eddy-current losses has been eliminated.

The matter is of importance in practice in the iron behind the teeth of the rotating armatures of electrical machines. In the teeth themselves the flux is mainly an alternating one, but at any point in the iron behind the teeth the flux will rotate with respect to the iron. The hysteresis loss occurring behind the teeth will on this account not be the same as that which occurs for an alternating flux. This is a point of some interest, since it prevents an accurate predetermination of the iron loss being made on the basis of the specific loss figures obtained in an alternating-current test of the material. The problem in practice is further complicated by the fact that the rotating flux is not constant in magnitude but may be considered to be a combination of a constant rotating flux and an alternating flux. The present investigation deals only with a constant rotating flux.

CASE OF A SINGLE DISC SAMPLE

If a magnetically isotropic single disc is suspended at its centre in a horizontal plane containing an applied field, then, in the absence of eddy currents, a uniform torque will be required to rotate the disc and the work done in one revolution will represent the rotational hysteresis loss per cycle. If H is the applied field and J the intensity of magnetization, J will lag H by an angle α such that the torque is equal to $HJ \sin \alpha$ per cm³ of the material. The loss per cm³ per cycle is therefore $2\pi HJ \sin \alpha$. It has been shown† that α and hence the rotational hysteresis loss per cycle is independent of the speed of rotation of the disc. In an isotropic disc, then, we might determine the rotational hysteresis loss by simply measuring the torque required to move the disc in one direction of rotation in an applied field. The rate of rotation can be brought to zero at the time of measurement so that eddy-current losses are not involved. This method was used by von Harlem‡ to measure the relation between the angle α and the magnetization in the case of a magnetically-hard tungsten steel.

Rolled sheets, however, are invariably characterized by considerable variation of the magnetic properties in different directions in the sheet. A disc cut from a rolled sheet will, on this account, be acted on by a torque which alternates in direction with respect to the angle of rotation. In the case of the magnetically-soft commercial electrical sheet materials this torque may reach a value, depending on the material and the magnetization considered, of the order of one hundred or more times the mean torque due to hysteresis. This complication makes it impracticable to measure rotational hysteresis loss directly by torque measurements on a single disc, except perhaps at low flux densities.

---

* The Papers Committee invite written communications, for consideration with a view to publication, on papers published in the *Journal* without being read at a meeting. Communications (except those from abroad) should reach the Secretary of The Institution not later than one month after publication of the paper to which they relate.

† See Bibliography, (1). ‡ *Ibid.*, (2). § *Ibid.*, (3). ‖ *Ibid.*, (4).

† See Bibliography, (5). ‡ *Ibid.*, (6).

The difficulty is, however, readily overcome by an expedient for the understanding of which it is necessary to consider the main cause of magnetic anisotropy in sheet steel.

MAGNETIC ANISOTROPY IN SHEET STEEL

Iron, in common with most metals, crystallizes on the cubic system. Fig. 1 shows the magnetization curves obtained by Honda and Kaya[*] for a single crystal of iron, measured parallel to a cube edge, to the diagonal of a cube face, and to the long diagonal of the cube, respectively. Similar curves have recently been obtained by Williams[†] for a 3·85 % silicon steel.

Hence if the crystal is magnetized by an applied field the stored energy is dependent on the direction of magnetization. For saturation conditions this is given[‡] by

$$W = K_0 + K_1(S_1^2S_2^2 + S_2^2S_3^2 + S_3^2S_1^2) + K_2(S_1^2S_2^2S_3^2) \quad (1)$$

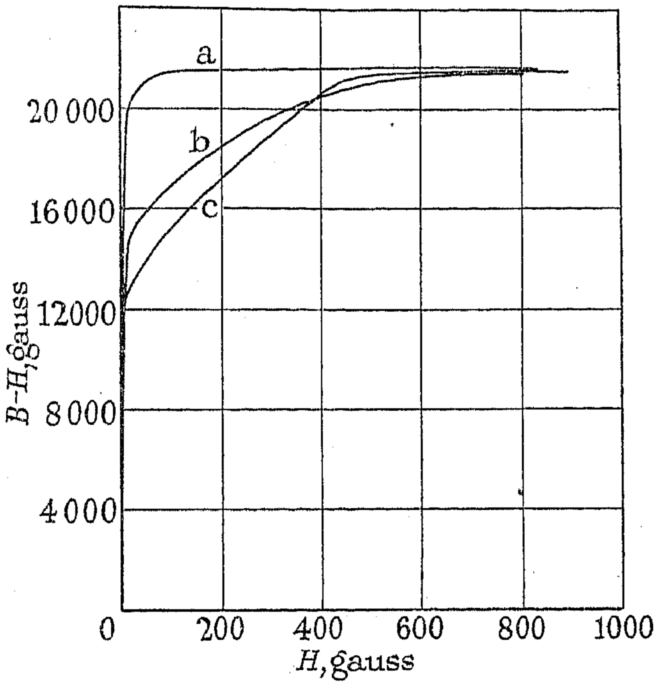


Fig. 1.—Magnetization curves for single crystal of iron (Honda and Kaya).

Curve *a*: For *H* parallel to cube edge.
Curve *b*: For *H* parallel to diagonal of cube face.
Curve *c*: For *H* parallel to long diagonal of cube.

where K_0, K_1, and K_2, are constants and S_1, S_2, and S_3, are the direction cosines of the direction of the intensity of magnetization relative to the principal axes of the cubic crystal.

Hence the crystal, in an applied field, will experience a torque acting to restore it to a position of minimum stored energy, which, in the case of iron, is for the magnetization parallel to a cube edge. The torque acting in a particular case is readily deduced[§] for saturation conditions from (1).

The torque equations for three particular crystal orientations, designated A, B, and C respectively in Fig. 2, and which are important in rolled sheets, are given below.

Orientation A.—Suppose a thin disc (or preferably an oblate ellipsoid of revolution) is cut from a single crystal in the plane of the cube face *abcd*, Fig. 2, and suppose the datum diameter is parallel to a cube edge *ad*. Then if this disc is rotated about its perpendicular axis in a high saturating field in the plane of the disc the torque acting per cm³ of the material is given by

$$L_A = -\tfrac{1}{2}K_1 \sin 4\alpha$$

where α is the angle between the saturation intensity J_0 and the datum line.

Orientation B.—If the datum line is taken as the diagonal *ac* of the cube for the disc in A, then

$$L_B = \tfrac{1}{2}K_1 \sin 4\alpha$$

Orientation C.—If the disc is cut in the plane *acef* and the cube edge *af* is taken as the datum line, then

$$L_C = -\frac{K_1}{8}(2 \sin 2\alpha + 3 \sin 4\alpha) - \frac{K_2}{64}(\sin 2\alpha + 4 \sin 4\alpha - 3 \sin 6\alpha)$$

In the case of polycrystalline sheets the action of hot or cold rolling in conjunction with the subsequent heat treatment causes a large percentage of the crystals in the sheet to orient themselves in preferred directions. Examination of magnetically soft rolled sheets by X-ray[*] and light-reflection[†] methods has shown that the orientations generally found are very near to those represented by A, B, and C, above, where the datum line and plane correspond to the rolling direction and the plane of the sheet respectively.

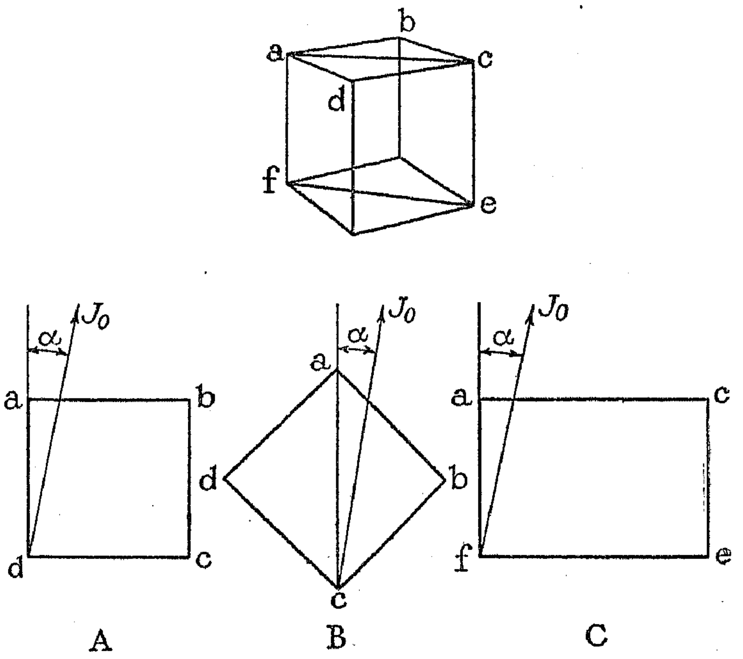


Fig. 2.—A cubic crystal and 3 particular crystal orientations

Clearly if a polycrystalline disc cut from such a sheet has *n* % of the material with Orientation A and *m* % with Orientation C, the remainder being oriented at random, then the torque per cm³ for the saturated disc, neglecting the hysteresis component, is given by

$$L = \frac{n}{100}L_A + \frac{m}{100}L_C$$

---

[*] See Bibliography, (7). [†] *Ibid.*, (8). [‡] *Ibid.*, (9). [§] *Ibid.*, (10).

[*] See Bibliography, (11). [†] *Ibid.*, (12).

Theoretical torque curves for different proportions of A and C and of B and C are shown in Figs. 3 and 4 respectively for iron, using the approximate known values $K_1 = 4 \times 10^5$, $K_2 = 2 \times 10^5$ ergs per cm^3 Comparatively high torques are seen to be involved. Experimental torque curves obtained on single discs of commercial electrical sheet iron and silicon steel can usually be fitted quite closely by a curve of one of these types Examples may be seen in Figs. 8 and 9.

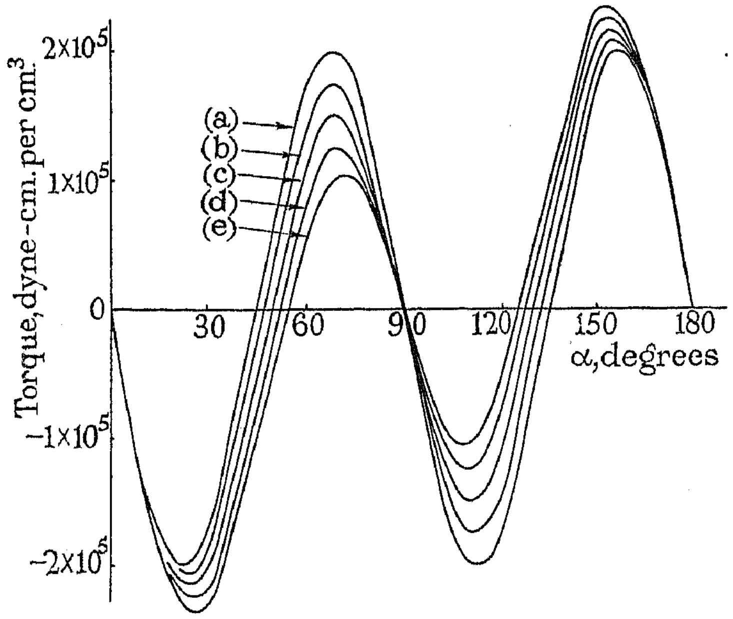


Fig. 3.—Theoretical torque curves for:—

(*a*) 100 % of crystals with Orientation A.
(*b*) 75 % of crystals with Orientation A plus 25 % with Orientation C.
(*c*) 50 % of crystals with Orientation A plus 50 % with Orientation C.
(*d*) 25 % of crystals with Orientation A plus 75 % with Orientation C.
(*e*) 100 % of crystals with Orientation C.

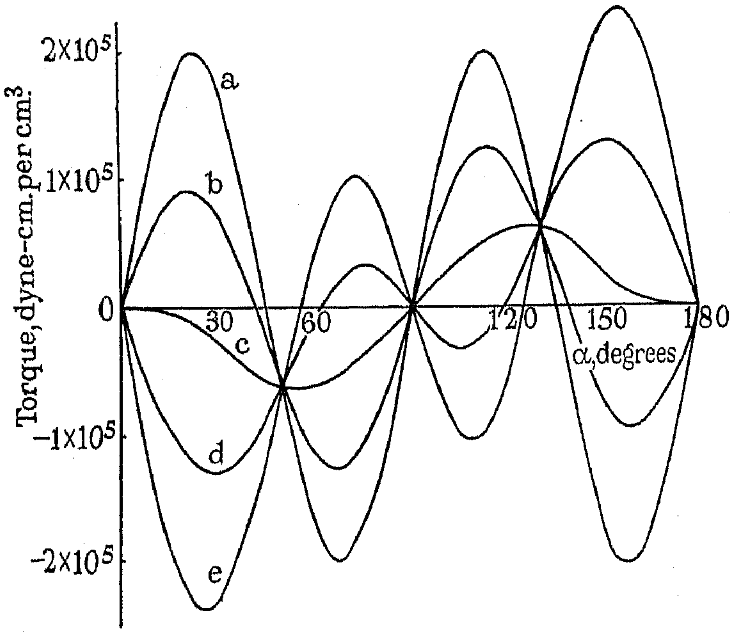


Fig. 4.—Theoretical torque curves for:—

(*a*) 100 % of crystals with Orientation B.
(*b*) 75 % of crystals with Orientation B plus 25 % with Orientation C.
(*c*) 50 % of crystals with Orientation B plus 50 % with Orientation C.
(*d*) 25 % of crystals with Orientation B plus 75 % with Orientation C.
(*e*) 100 % of crystals with Orientation C.

METHOD OF MEASUREMENT OF ROTATIONAL HYSTERESIS LOSS

It will be clear from the foregoing that, neglecting hysteresis, the torque per cm^3 exerted on a thin disc in an applied saturating field is given quite generally by

$$L = D \sin 2(\alpha + \delta_2) + E \sin 4(\alpha + \delta_4) + F \sin 6(\alpha + \delta_6) \quad (2)$$

where D, E, F, δ_2, δ_4, and δ_6 are constants depending on the material and the particular crystal arrangement. At magnetizations below saturation the amplitude of the torque is reduced, but it may still be expressed by an equation of the same form.

If now three identical discs are superimposed so that corresponding diameters on the discs are relatively displaced at angles of 0°, 120°, and 240° respectively, then the torque per cm^3 for the composite disc will clearly be given by

$$L = F \sin 6(\alpha + \delta_6)$$

The torque due to anisotropy has therefore been reduced to that corresponding to the last term of equation (2). This might also be eliminated by increasing the number of discs, but, fortunately, this term is usually small enough to render this unnecessary.

If now we include the torque L_H per cm^3 due to the rotational hysteresis loss, then we have for one direction of rotation of the disc

$$L_1 = F \sin 6(\alpha + \delta_6) + L_H$$

and for the reverse rotation

$$L_2 = F \sin 6(\alpha + \delta_6) - L_H$$

The mean torque due to hysteresis is obtainable by taking the mean value of either L_1 or L_2 over a complete revolution of the composite disc. More conveniently it may be obtained from the mean value of $\frac{1}{2}(L_1 - L_2)$.

The method used in the present investigation comprises the use of a test sample made up of three discs as described above, the rotational hysteresis loss being determined by measuring the average torque required to rotate the sample in an applied field. In practice, owing to small differences in the discs, inaccuracies in relative alignment, and perhaps some inequality in flux distribution, the first two terms of equation (2) are not completely eliminated. The following numerical example taken from the results given later for Sample 1 shows, however, the benefit to be gained from a composite disc. At $B = 22\,600$ gauss the maximum torque for a single disc is about 35 000 dyne-cm. per cm^3 The mean torque due to hysteresis is only 415 dyne-cm. per cm^3, or 1·2 % of the peak torque. With the composite disc the maximum torque is about 1 800 dyne-cm. per cm^3 Loss measurements on the single disc would clearly be impracticable, but with the multiple disc some 20 times the sensitivity can be made use of and there is no difficulty.

APPARATUS AND PROCEDURE

To make up a test sample, three $2\frac{1}{2}$-in. squares were cut from near each other in a strip of the material to be tested. Discs $1\frac{1}{4}$ in. diameter were then cut by mounting the squares in turn on a block in a lathe and using a sharp cutting tool. A line scribed on the strip before cutting gave corresponding datum lines on the discs.

Many forms of torque magnetometer[*] have been used for the measurement of the torque curves of discs and ellipsoids. The instrument used in the present case is shown in Fig. 5. Sample D is clamped between the brass discs B, the whole being capable of rotation on the spindles S in the journal jewel bearings J. This moving system is suspended by the phosphor-bronze torsion wire W from the adjusting screw C locked to the top of the brass tube T. The latter has a collar O soldered to it, enabling it to be rotated in the supporting frame F, and a pointer P attached to it at the lower end moves over the graduated aluminium disc A attached to the upper spindle S.

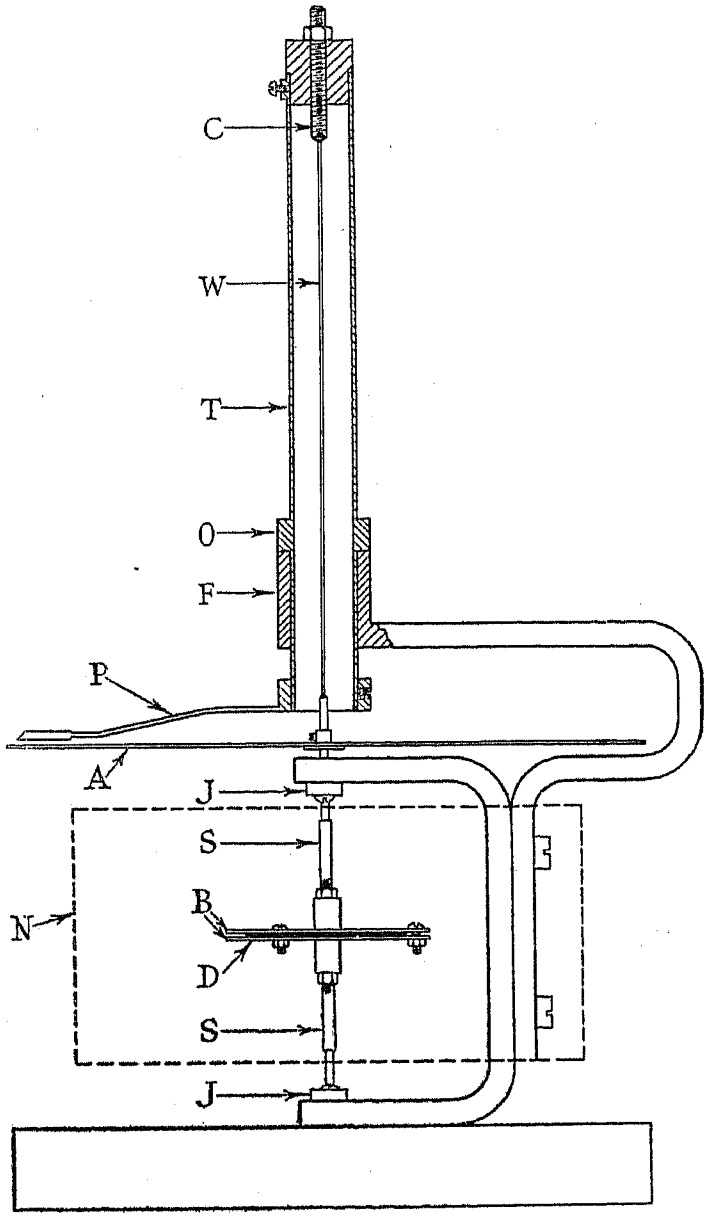


Fig. 5.—Torque magnetometer.

The suspensions used varied in diameter from about 0·01 in. to 0·022 in., depending on requirements, and were about 4½ in. long. The torque constant was determined, in known manner, from the time of swing of the moving system with and without a known added moment of inertia.

The applied field was obtained by an electromagnet the pole-faces of which, shown at N, were 2 in. deep, 4 in. wide, and 2 in. apart. An applied field up to $H = 2\,800$ gauss could be obtained.

The angular position of the disc relative to the direction of the applied field was read on the aluminium disc A by a fixed pointer (not shown).

It will be seen that the sample may be rotated by the tube T by the fingers, the angular position of the disc being read by the fixed pointer, and the twist in the suspension by the moving pointer.

For any given value of the applied field the procedure was to rotate the sample in a clockwise direction, through one revolution, to a definite position of the disc in the field, and then take a reading of the torque. The disc was then rotated through one revolution in a counter-clockwise direction to the same final position and the torque again read. The difference of these readings is clearly equal to twice the torque due to hysteresis. This procedure was then repeated for successive positions of the disc. The torque required is, of course, that which will just bring the disc round to the desired position for rotation in the appropriate direction. Obviously if this position is overshot it is necessary to rotate through a further 360° before taking a reading.

It will be noted that frictional forces on the moving system act in the same direction as the torque due to hysteresis, and it is essential that these forces should be negligibly small. To this end, journal jewel bearings were used in the instrument. The frictional torque was unreadably small with the most sensitive suspension employed in the tests, provided the apparatus was tapped lightly with the finger during reading.

MEASUREMENT OF *B* AND *H*

The values of B and H for the composite disc were obtained ballistically. A coil of 20 turns of 0·007 in. enamel-covered copper wire was close-wound round a diameter of the sample, the area embraced by the coil being kept as low as possible to reduce air-flux corrections. The sample was mounted in its holder with spindles attached, but removed from the instrument, and with the coil perpendicular to the direction of the applied field the sample was suddenly rotated through 180° and the change of flux linkages due to the reversal was measured by a ballistic galvanometer. The applied field, with the sample removed, was similarly measured by reversal of a suitable search coil.

The following relations may then be shown[*] to hold very nearly:—

$$B' = \frac{k\theta}{2A_sT}$$

$$B = \left\{1+\frac{N}{4\pi}\left(\frac{A_c}{A_s}-1\right)\right\}B' - \left(1+\frac{N}{4\pi}\cdot\frac{A_c}{A_s}\right)\left(\frac{A_c}{A_s}-1\right)H'$$

$$J = \left(1+\frac{N}{4\pi}\cdot\frac{A_c}{A_s}\right)\frac{B'}{4\pi} - \left(1+\frac{N}{4\pi}\cdot\frac{A_c}{A_s}\right)\frac{A_c}{A_s}\cdot\frac{H'}{4\pi}$$

$$H = \left(1+\frac{N}{4\pi}\cdot\frac{A_c}{A_s}\right)\left(H' - \frac{NB'}{4\pi}\right)$$

where B' = apparent flux density.
B = true flux density.
J = intensity of magnetization.
H' = applied field.

---

[*] See Bibliography, (13).

[*] See Bibliography, (7).

H = effective field in the material.
k = flux linkages per unit deflection of the galvanometer.
θ = mean deflection of the ballistic galvanometer for the reversal.
A_s = cross-sectional area of the disc under the coil.
A_c = mean cross-section embraced by the B coil.
T = number of turns on the B coil.
N = demagnetizing factor for the sample.

Moreover it may be shown* that, for the materials in question, the demagnetizing factor is given very nearly by

$$\frac{4\pi}{N} = \text{the initial slope of the } B'/H' \text{ curve} \quad . \quad . \quad (3)$$

DISCUSSION OF ACCURACY

To give some idea of the order of magnitude of the corrections and quantities involved, the following typical values (for Sample 2) are given:—

$$\frac{A_c}{A_s} = 1\cdot36 : \quad \frac{N}{4\pi} = 0\cdot0345$$

giving $$B = 1\cdot012B' - 0\cdot377H'$$

and $$H = 1\cdot047(H' - 0\cdot0345B')$$

The correction to be applied to B' to obtain the true value B is greatest at the highest induction, falling rapidly as the induction falls. For the highest induction measured in Sample 2, $B' = 22\,800$ and $B = 22\,060$ gauss, H' being 2 750 and H 2 050 gauss. It will be seen that uncertainty in the values of A_c/A_s and N does not materially affect the values of B, since the maximum correction to B' is only 3·3 %. The relative measurements of B and H' are considered to be correct to about 1 %. The uncertainty in the value of N determined from equation (3) may be about the same amount. The estimated errors in H due to a 1 % error in N are 0·4 % at $H = 2\,000$, 6 % at $H = 100$, and 50 % at $H = 10$ gauss. Obviously a relative inaccuracy of 1 % between corresponding values of H' and B' leads to errors in H of the same order. On account of these circumstances observations of H are only of value, for the materials in question, for inductions over about 15 000 gauss.

It is considered that the torque measurements had an absolute accuracy of about 1 %. For the first portion of the rotational hysteresis loss curves, up to and rather beyond the peak of the curves, the relative accuracy of the loss measurements is considered to be about 1 %. On the last part of the curves, near saturation, the accuracy is not so good, mainly because there is, as already indicated, a residual anisotropic torque. In the case of Samples 1, 2, and 3, the last values are probably accurate to about 6 %. For the final readings in the case of Sample 4 there was a large sin 6α component in the residual torque, and the torque due to hysteresis was also small. For this reason the last two or three values are accurate to probably not more than 30 or 40 %.

A further point to be considered is the question of uniformity of flux in the composite disc. The measurements made obviously give only the mean value of B over the whole sample in the direction of the diameter normal to the B coil. But for the first portion of the magnetization curve, up to, say, $B = 13\,000$ or 14 000 gauss, the effective field H in the material is small compared with the demagnetizing field NJ. The average magnetization in the sample is therefore dependent only on the applied field and is independent of the permeability of the sample. We may then expect the average induction in the sample, as it is rotated in the applied field, to remain constant, in spite of the variation in permeability in different directions which is known to exist in the material. There may, however, be non-uniformity of flux density in the sample for any particular position of the sample in the applied field. This may be due to the fact that the sample is not in the form of an isotropic ellipsoid of revolution but in the form of a composite disc. To introduce any serious error, however, this non-uniformity would require to be very large, since the relation between loss and flux density is found to be almost a linear one, for the first portion of the magnetization curve under consideration.

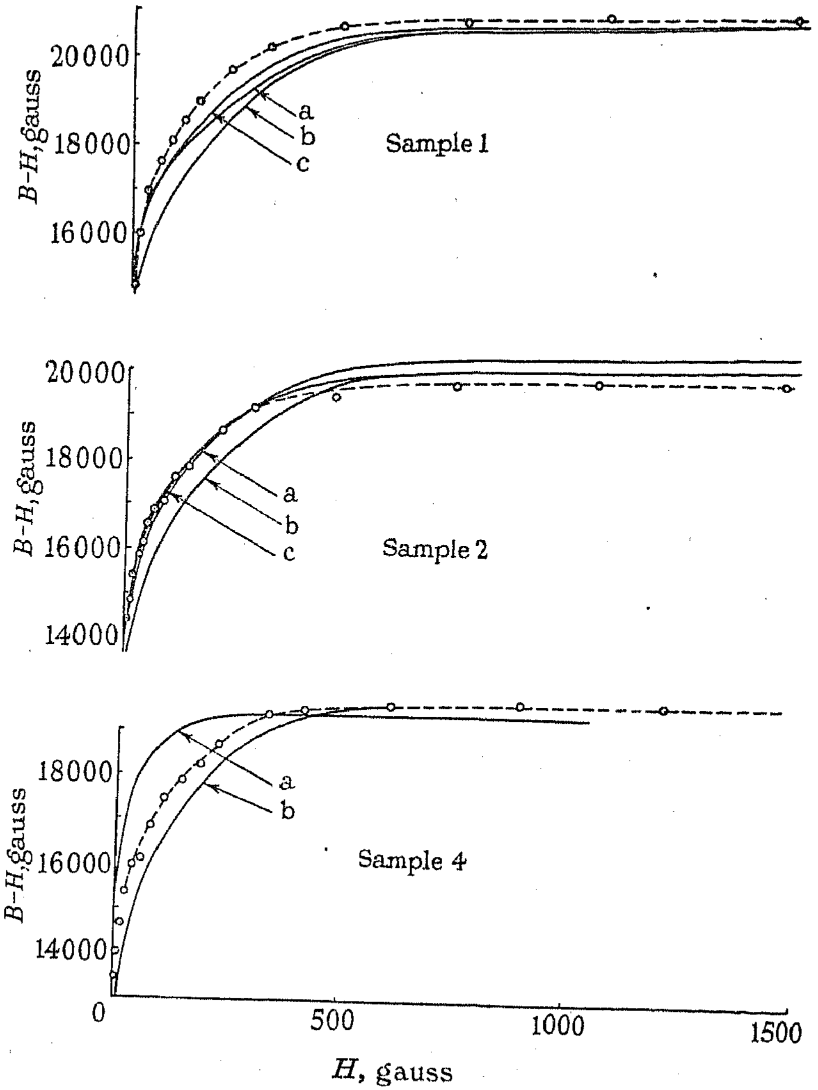


Fig. 6.—Magnetization curves obtained on strips in a permeameter and on composite disc samples.

a. Strips cut along rolling direction.
b. Strips cut across rolling direction.
c. Strips cut at 45° to rolling direction.
Dotted curves are of disc samples.

Above the knee of the magnetization curve the effective field becomes of the same order of magnitude as the demagnetizing field, and for a constant applied field the induction in the individual discs will vary as the disc is

---

* See Bibliography, (14).

Table 1

Sample number	Designation	Chemical analysis				
		C	Si	Mn	S	P
1	Ordinary electrical dynamo sheet ..	0·05	0·13	0·28	0·037	0·026
2	Higher-quality dynamo sheet	0·04	1·91	0·26	0·027	0·030
3	Ordinary transformer silicon steel ..	0·04	3·72	0·11	0·004	0·018
4	Cold-rolled transformer silicon steel ..	0·04	3·13	0·05	0·003	0·008

rotated. The variation in different directions as measured on strips of the material of Samples 1 and 2 (Sample 3 is known to be similar) in a standard permeameter is shown in Fig. 6. It is not considered that the variation from the mean flux density in the sample can greatly exceed the range of variation shown in these curves, say ± 1½ %, except possibly near the periphery of the discs. Such a variation would cause no appreciable error in the observed relation between loss and flux density. In the case of Sample 4, however, the variation is seen to be greater, and the non-uniformity in the neighbourhood of $H = 100$ gauss may be about ± 7 %. Here again the error caused must be much less than this.

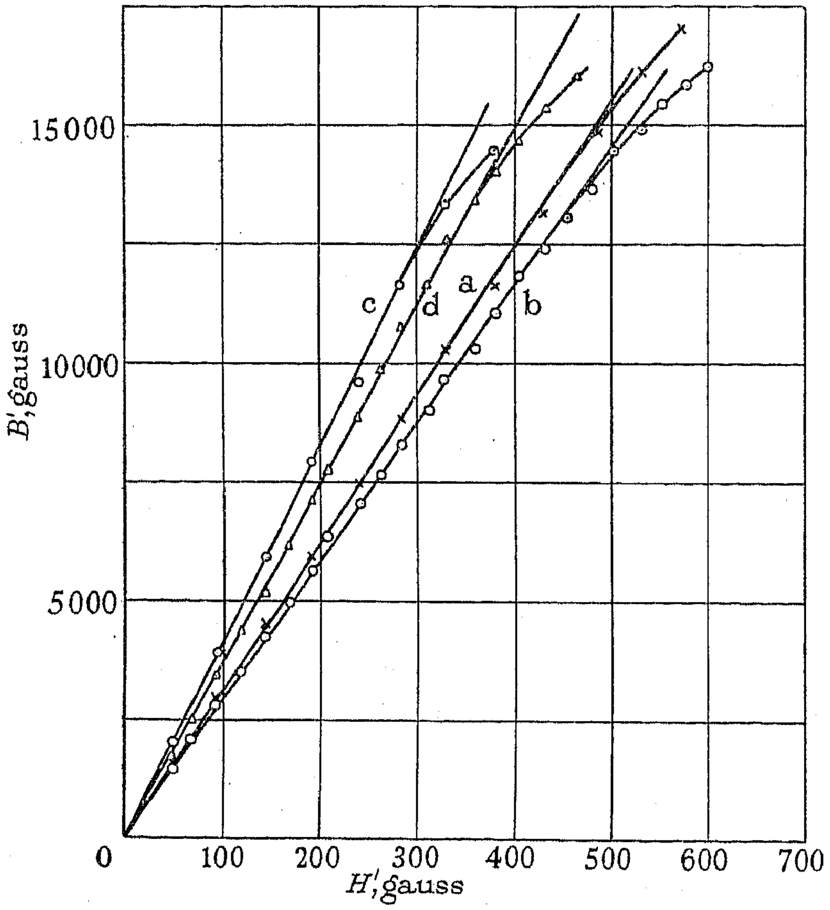


Fig. 7.—Determination of demagnetizing factors.

a. Sample 1: $N = 0{\cdot}405$.
b. Sample 2: $N = 0{\cdot}433$.
c. Sample 3: $N = 0{\cdot}304$.
d. Sample 4: $N = 0{\cdot}337$.

EXPERIMENTAL RESULTS

The chemical analyses of the materials investigated, and the dimensions of the discs, are given in Tables 1 and 2 respectively.

The demagnetizing factors for the disc have been obtained experimentally, using equation (3), from the initial straight-line portion of the B'/H' curves, and the observed values are given in Fig. 7. The demagnetizing factors have also been calculated, on the assumption that the disc sample approximates to an ellipsoid of revolution in which the ratio of minor to major axes is the same as the ratio of thickness to diameter of the discs. When this ratio is small we may write

$$N = 2\pi\frac{a}{c}\left\{\arcsin\left(1 - \frac{1}{2}\cdot\frac{a^2}{c^2}\right) - \frac{a}{c}\right\}$$

where a/c is the ratio of minor to major axis. The calculated and observed values are given in Table 2 for comparison.

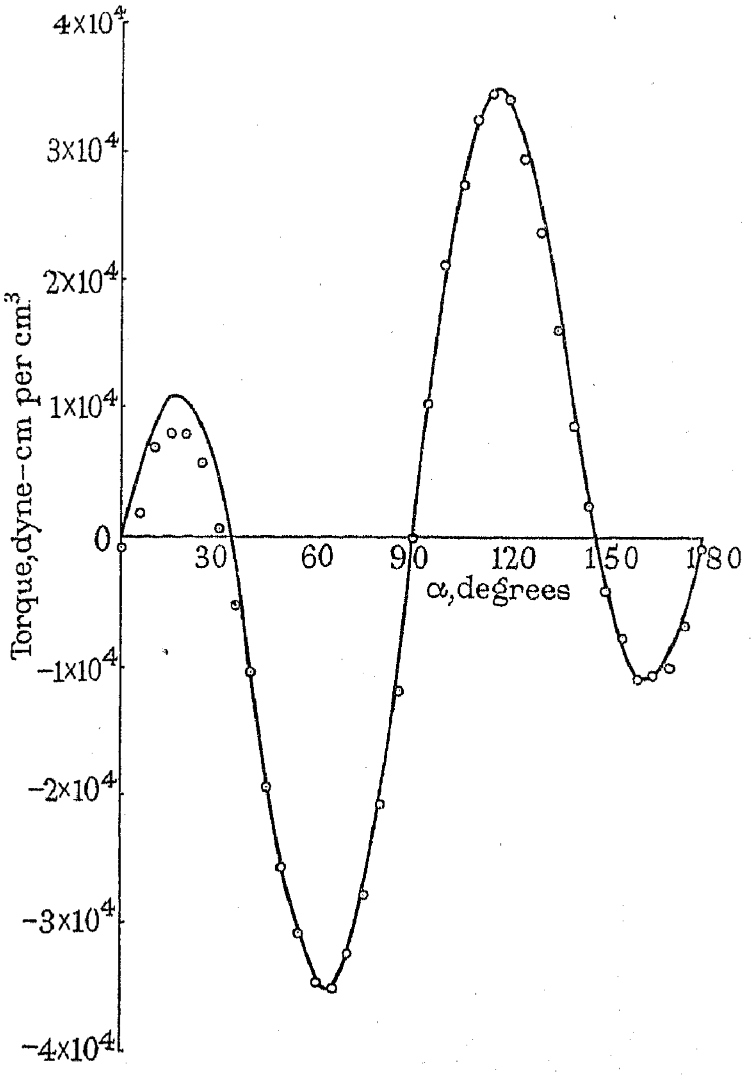


Fig. 8.—Torque curve on single disc of Sample 1.

o————o Observed points.
Full line is calculated curve.

Table 2

Sample number	Composite disc			Demagnetizing factor N		
	Diam.	Total thickness		Calculated using		Observed
		By weight	By micrometer	Thickness by weight	Thickness by micrometer	
	in.	in.	in.			
1	1·23	0·0486	0·052	0·370	0·39	0·405
2	1·19	0·0500	0·052	0·393	0·41	0·433
3	1·24	0·0347	0·037	0·289	0·31	0·304
4	1·23	0·0388	0·040	0·299	0·31	0·337

As already indicated, an exact knowledge of N is not required in the measurement of B, but only to determine the effective field H in the disc. The observed magnetization curves for the discs are shown in Fig. 6. The corresponding curves, obtained on strips cut in different directions from the sheets from which the discs were taken, are also shown.

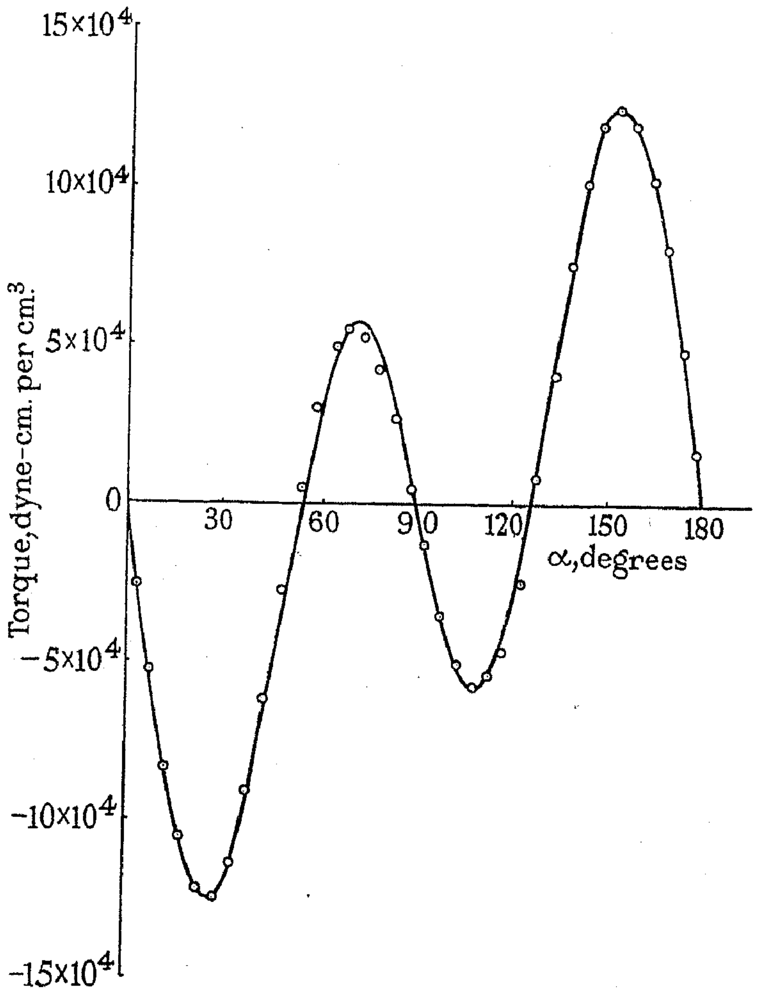


Fig. 9.—Torque curve on single disc of Sample 4.
o———o Observed points.
Full line is calculated curve.

The experimental torque curves obtained on single discs of Samples 1, 2, and 3, which are all hot-rolled materials, were very similar. The observed points for a single disc of Sample 1 are shown in Fig. 8, for an applied field of 2 440 gauss. The curve drawn has the equation

$$\frac{L}{10^4} = -\ 1{\cdot}80 \sin 2\alpha + 2{\cdot}14 \sin 4\alpha + 0{\cdot}17 \sin 6\alpha$$

and is seen to fit the observed points fairly closely. If we take $K_1 = 4 \times 10^5$ and $K_2 = 2 \times 10^5$ ergs per cm³ this curve represents the theoretical torque under saturation conditions of a material having 24·6 % of the crystals with Orientation B, 17·4 % with Orientation C, and the remainder at random.

Fig. 9 gives the corresponding quantities for Sample 4, which is a cold-rolled material. This curve has the equation

$$\frac{L}{10^4} = -\ 5{\cdot}20 \sin 2\alpha - 8{\cdot}88 \sin 4\alpha + 0{\cdot}47 \sin 6\alpha$$

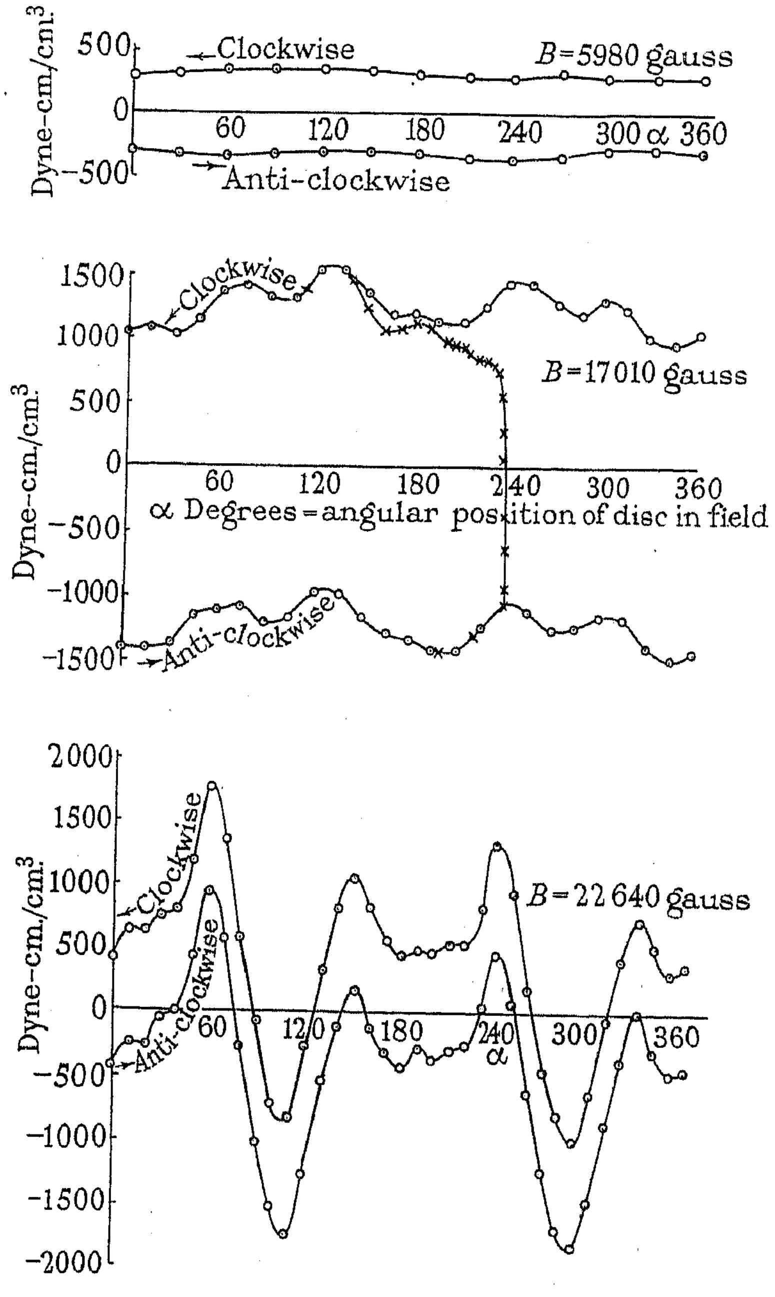


Fig. 10.—Torque curves for composite disc: Sample 1.

corresponding to a crystal arrangement of 4·7 % Orientation A, 67·2 % Orientation C, and the remainder at random. K_1 and K_2 have been taken* in this case to be 3×10^5 and $1{\cdot}5 \times 10^5$ ergs per cm³ respectively.

It will be seen that the experimental torque curves are given quite closely by an equation of the theoretical form of equation (2), and it is not important for the purposes of the present investigation whether the true crystal arrangement is that corresponding to the values given above or not.

---

* See WILLIAMS, Bibliography, (8) and (13); also TARASOV and BITTER, Bibliography (13).

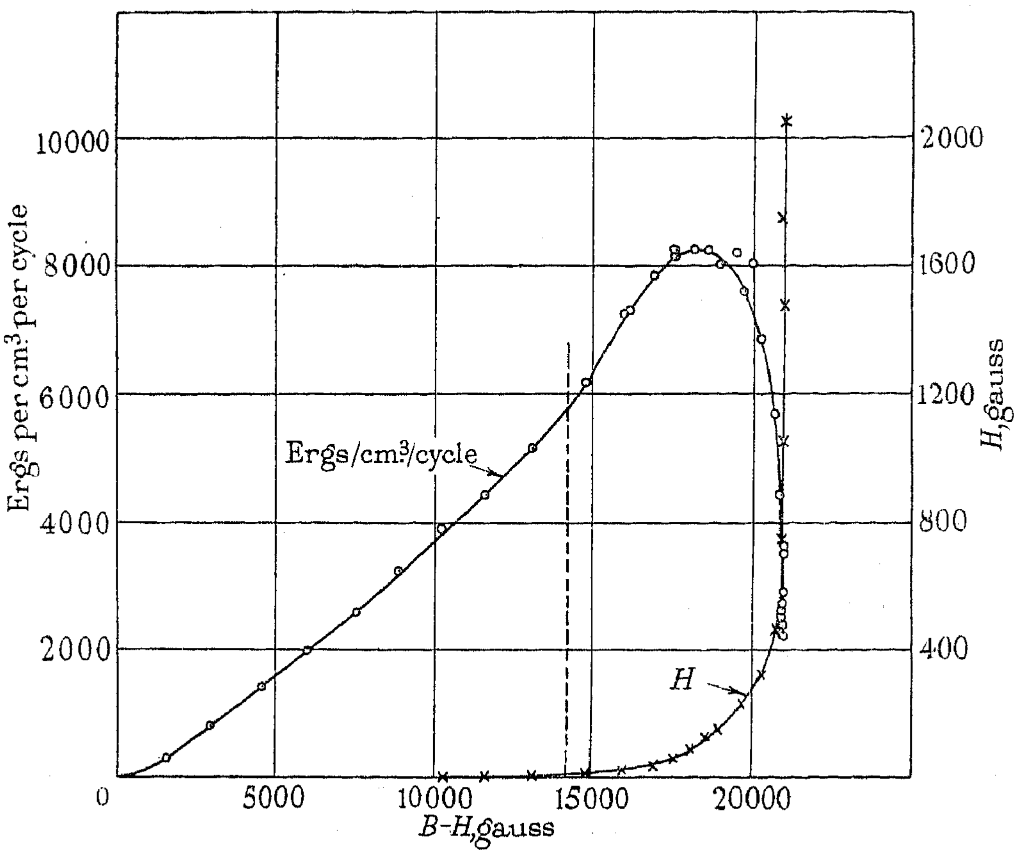


Fig. 11.—Rotational hysteresis loss and magnetization curve for Sample 1.

The torque curves for clockwise and anti-clockwise rotation in the case of the composite Sample 1 are shown in Fig. 10 for three values of the applied field corresponding to flux densities of 5 980, 17 010, and 22 640 gauss respectively. The rotational hysteresis loss corresponding to these flux densities is represented by half the area between these curves.

The way in which the torque varies when the sample is first rotated anti-clockwise and then reversed in rotation may also be seen in Fig. 10 for $B = 17\ 010$ gauss.

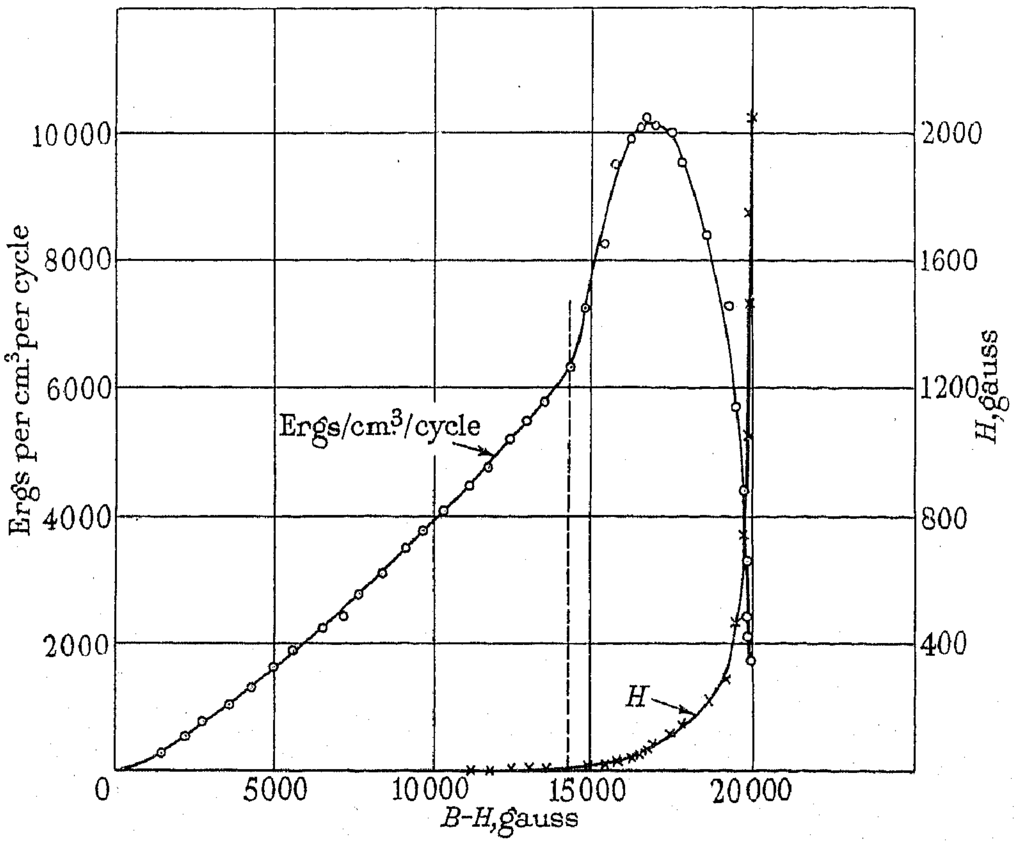


Fig. 12.—Rotational hysteresis loss and magnetization curve for Sample 2.

The complete curves of rotational hysteresis loss for the four materials are shown in Figs. 11 to 14, plotted with B–H as abscissae. The magnetization curves are also shown, plotted for convenience to the same base.

DISCUSSION OF RESULTS

Examination of the loss curves shows certain well-marked points of similarity in the four cases. The loss at low flux densities, below $B = 1\ 000$ gauss, say, is seen to increase comparatively slowly, although this region has not been investigated in detail. Thereafter, and up

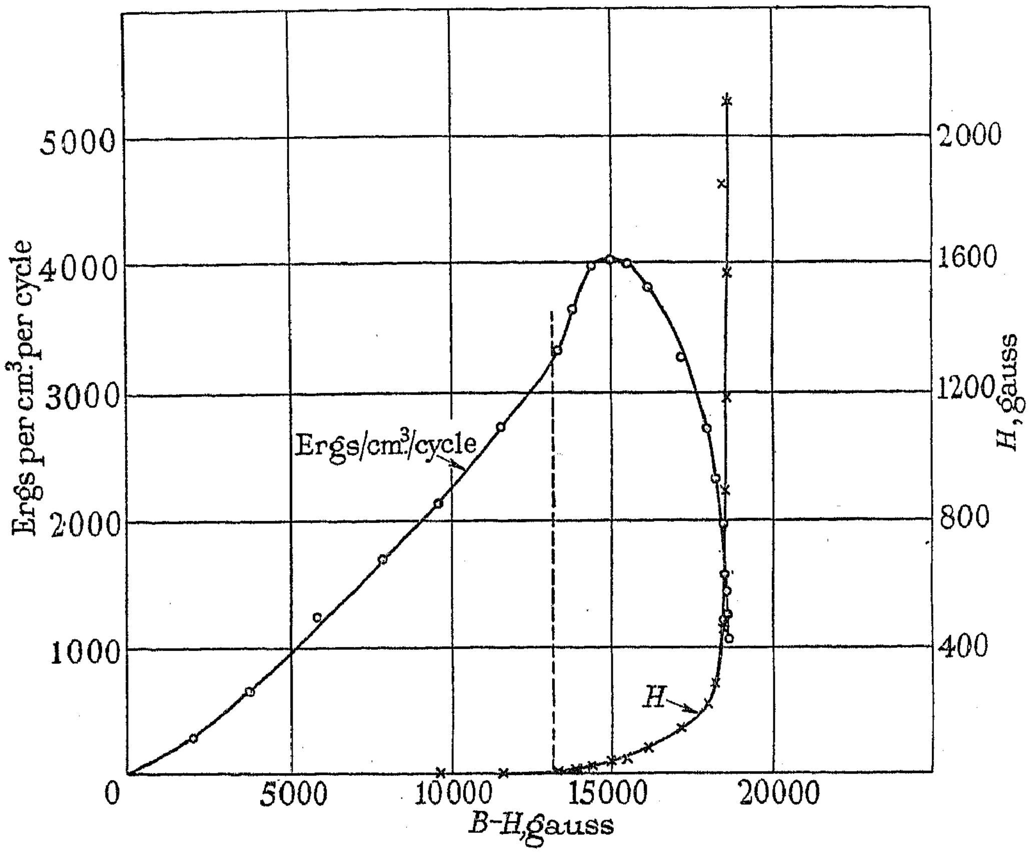


Fig. 13.—Rotational hysteresis loss and magnetization curve for Sample 3.

to a flux density of about 0·7 of the saturation value of *B–H*, the loss increases with *B–H*, not quite linearly but at a slightly faster rate. Above this density there is a sharp increase in the loss, which rises to a maximum in the region of 0·8 to 0·85 of the saturation value of *B–H* and then falls rapidly towards zero. The tests were carried out up to a maximum applied field of $H = 2\,800$ gauss. The lowest value of loss reached was that for the cold-rolled Sample 4, which is down to about 6 % of the maximum loss attained for this material.

The sharp rise in loss at about 0·7 of the saturation value of *B–H* has not, so far as the author is aware, previously been observed. This sharp rise is noticeable in all the samples and is particularly marked in the case of Sample 2. It will be seen in all cases that this sudden change occurs at a value of *B–H* in the region of the

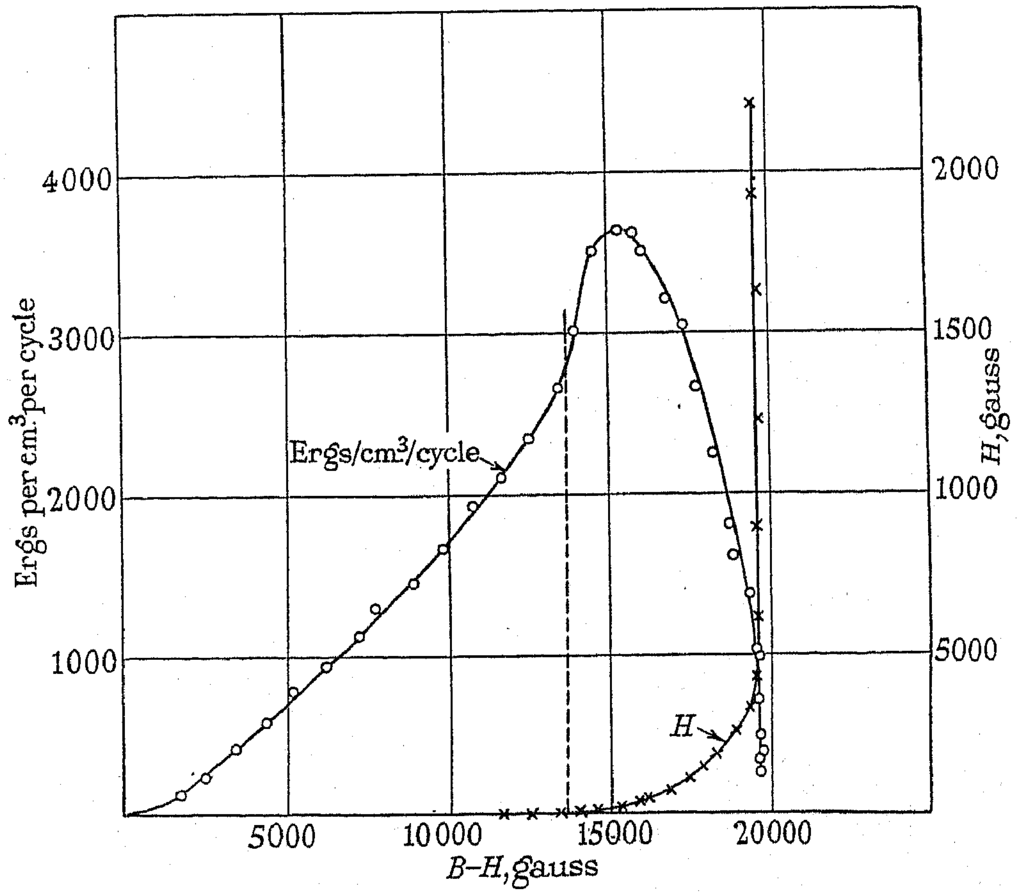


Fig. 14.—Rotational hysteresis loss and magnetization curve for Sample 4.

"knee" of the magnetization curve, i.e. at the point where H begins to rise rapidly with respect to $B-H$.

This relation between the loss and magnetization curves may, perhaps, be explained on the basis of certain considerations relating to the domain theory* of ferromagnetism. According to this theory magnetization below the knee proceeds in steps, corresponding to the Barkhausen discontinuities, each step representing a reversal or sudden change in direction through 90° of the spontaneous saturation magnetization in a domain. There may be, in addition, a parallel reversible process,† or *Schrumpfprozess*, involving no hysteresis loss. For any particular domain the sudden change in direction may be expected when a certain value of the field acting on it in the final direction of its magnetization has been reached. The total change in energy involved in this discontinuous change is then a function of the volume of the domain, the saturation intensity, and the effective field. Certain considerations make it probable that the whole of this change of energy is not dissipated as heat, but only a portion of it. However, the point is that one may expect the heat dissipated as hysteresis loss to be a function of H in both the alternating and the rotational case. At the knee of the magnetization curve the field required to produce the discontinuous rotation has already been reached or exceeded for most of the domains, and these domains contribute further to the total magnetization on a further large increase of H, by a rotation‡ of the spontaneous magnetization in the domains from the "easy" direction towards the direction of the applied field. There are some domains remaining, however, which are not acted upon until H has increased beyond its value at the knee.§ The contribution to the magnetization due to these domains is only that corresponding to their volume, but the contribution to the loss is high on account of the high values of H at which the sudden change in direction of the magnetization occurs. The loss will therefore rise steeply with increase of magnetization.

Similar ideas may be applied to the portion of the loss curve near saturation. For a very high field the spontaneous magnetization is always in the direction of the field, and as the field is rotated it rotates smoothly and without the discontinuities which result in hysteresis loss. Hence the loss may then be expected to be zero. At lower fields the discontinuities can occur again during rotation of the field, causing, at first, an increasing loss for decreasing H. In this case the loss will be dependent on the anisotropic constants K_1 and K_2, as well as on H and on the value of the spontaneous saturation intensity of magnetization.

The above indicates in a qualitative manner how the observed rotational hysteresis loss might be explained on the basis of the domain theory and the magnetic anisotropic properties of the materials. Satisfactory quantitative calculations have, however, not been made.

ACKNOWLEDGMENTS

The author wishes to record his indebtedness to Mr. H. T. W. Wilding, for assistance with the flux measurements; to Dr. C. Dannatt, who introduced the author to the subject of magnetic anisotropy in sheet metal; to Mr. B. G. Churcher, for his interest and encouragement throughout the investigation; and to Dr. A. P. M. Fleming, C.B.E., Director and Manager of the Metropolitan-Vickers Electrical Company's Research and Education Departments, and to the Company, for permission to publish the paper.

BIBLIOGRAPHY

(1) F. G. Baily: *Philosophical Transactions of the Royal Society*, 1896, vol. 187, p. 715.
(2) R. Beattie: *Philosophical Magazine*, 1901, vol. 1, p. 642.
(3) P. Weiss and V. Planer: *Journal de Physique*, 1908, vol. 6, p. 5.
(4) K. Seiyama: *Memoirs*, Kjushu University College of Engineering, 1930, vol. 5, p. 227.
(5) R. Gans and R. Loyarte: *Archiv für Elektrotechnik*, 1915, vol. 3, p. 139.
(6) J. von Harlem: *Annalen der Physik*, 1932, vol. 14, p. 667.
(7) K. Honda and S. Kaya: *Scientific Reports*, Tôhaku University, 1926, vol. 15, p. 721.
(8) H. J. Williams: *Physical Review*, 1937, vol. 52, p. 747.
(9) E. C. Stoner: "Magnetism and Matter," 1934, p. 392.
N. Akulov: *Zeitschrift für Physik*, 1929, vol. 54, p. 582.
G. S. Mahajani: *Philosophical Transactions of the Royal Society*, 1929, vol. 228, p. 63.
F. C. Powell: *Proceedings of the Royal Society*, A, 1930, vol. 130, p. 167.
(10) R. M. Bozorth: *Physical Review*, 1936, vol. 50, p. 1076.
(11) N. Akulov and N. Brüchatov: *Annalen der Physik*, 1932, vol. 15, p. 741.
(12) K. J. Sixtus: *Physics*, 1935, vol. 6, p. 105.
(13) O. Dahl and J. Pfaffenberger: *Zeitschrift für Physik*, 1931, vol. 71, p. 93.
H. J. Williams: *Review of Scientific Instruments*, 1937, vol. 8, p. 56.
L. P. Tarasov and F. Bitter: *Physical Review*, 1937, vol. 52, p. 353. *Also see* Items (11) and (12) above.
(14) W. L. Webster: *Proceedings of the Royal Society*, A, 1925, vol. 107, p. 496.
(15) N. S. Akulov: *Zeitschrift für Physik*, 1931, vol. 67, p. 794.
F. Bitter: "Introduction to Ferro-Magnetism," 1937, p. 182.
(16) R. M. Bozorth and J. F. Dillinger: *Physical Review*, 1930, vol. 35, p. 733.

---

* See Stoner: Bibliography, (9), p. 390.
† See Bibliography, (15). ‡ *Ibid.*, (15). § *Ibid.*, (16).

DISCUSSION ON
"MODERN SYSTEMS OF MULTI-CHANNEL TELEPHONY ON CABLES"*

THE AUTHORS' REPLY TO THE DISCUSSIONS AT LEEDS, BIRMINGHAM, LIVERPOOL, AND EDINBURGH

Col. A. S. Angwin and **Mr. R. A. Mack** (*in reply*): A number of the points touched upon in the discussions can only be elucidated as the result of more extended experience, and we feel that many of the speakers tend to lose sight of the shortness of the time that the 12-channel system has been in service and the experimental nature of the coaxial system. The decision to go forward with full-scale trials of the systems described was based on general economic and technical grounds rather than on detailed economic investigations, and experience under service conditions confirms the expectations of greater economy in the provision of trunk telephone circuits.

As stated in the paper, one of the reasons for installing the coaxial cable was the possibility of obtaining, at some future date, one or two channels for the transmission of television programmes, but the paper was concerned more with the provision of telephone circuits. Several speakers directed their inquiries towards the question of phase compensation. Phase and attenuation compensation together form perhaps the most difficult problem in the transmission of high-definition television signals over cables. Now that a block of telephone circuits is working on the London–Birmingham coaxial cable, effort is being concentrated on the problem of television transmission. There seems no practical possibility of transmitting high-definition television without allocating a band of at least $1\frac{1}{2}$ or 2 megacycles to each transmission.

Theoretically, each such band might be split into a number of narrower bands for transmission over separate channels or even separate lines, the bands being recombined at the point of reception. This has been shown, experimentally, to be possible to a limited extent. The greater the subdivision, however, the more the method becomes impracticable for reasons of complexity and cost.

The speed of transmission over the coaxial cable is about 180 000 miles per sec., not greatly different from the velocity of light. This gives a time of transmission for 400 miles of $2\frac{1}{4}$ millisec. The delay in terminal equipment and repeaters would not as much as double this time.

The use of tubular structures transmitting much higher frequencies than are at present contemplated for coaxial cables may enable a number of high-definition television transmissions to be passed over a single tube, but a large amount of research and development work will be necessary before this can be accomplished in a practical fashion. Mr. Terroni, we feel, is over-optimistic in suggesting that the hyper-frequency wave guide may come into commercial use within the next few years.†

Prof. Palmer in his remarks no doubt has in mind these same developments. Measurements so far made on the Post Office coaxial cables have not shown any effect such as he mentions.

The translation of television signals into the frequency range appropriate to the coaxial cable is carried out with a carrier frequency of the order of twice the highest frequency transmitted.

Phase compensation, so essential for television transmission, is not necessary for telephone circuits on the coaxial cable, and consequently the correction of attenuation distortion only has been undertaken in providing telephone circuits.

The possibility of complete breakdown of a coaxial system, with the consequent loss of some 300 or so circuits when the cable is fully equipped, is mentioned several times in the discussions. This is a disadvantage of the system which had to be taken into account when embarking on its development. As regards the penetration of water into the coaxial cable through a small hole in the sheath, due to corrosion, it is likely that the fall in insulation of the interstice pairs will give adequate warning. Serious mechanical damage is no more preventable than where an ordinary multi-conductor paper-insulated cable is concerned, though the stoppage is more likely to be complete in the coaxial case. Against breakdown of an intermediate repeater there is the insurance of automatic change-over to the spare repeater. The method of accomplishing this will be found outlined in the paper (see vol. 81, p. 589). The conditions of anode and filament voltage of the spare repeaters are indicated in our reply to the London discussion (see vol. 81, p. 605).

Owing to the high losses in each repeater section it would not be possible to work circuits with a faulty repeater strapped out. This applies to the 12-channel system as well as to the coaxial system.

The question of the power-handling capacity of an amplifier which is to transmit a large number of carrier channels is still a matter of theory which can be satisfactorily settled only as the result of practical trials which will become possible as systems such as the London–Birmingham coaxial cable are brought into use. So far as is known, the results of such practical trials are not yet available. This subject was referred to in our reply to the London discussion. The London–Birmingham system has been designed to transmit the high-frequency currents of the highest channel at approximately the same level as that at which the corresponding speech currents enter the trunk circuit. This, of course, is a very variable power, but, even making allowance for the lowest speech levels occurring in practice, attenuation by 50 db. during transmission along the line before reaching the input of the next repeater still leaves an adequate margin above the level of resistance noise (approximately 130 db. below 1 mW). The method of pre-equalization adopted for the coaxial system has certain advantages when the power-handling capacity and the gain of the repeaters are being used to their fullest extent. On the Bristol–Plymouth system the more normal, and on the whole more convenient, method of equalization has been adopted as it was possible to design repeaters, for this lower-frequency system, having a greater margin.

---

* Paper by Col. A. S. Angwin and Mr. R. A. Mack (see vol. 81, p. 573). For the discussions to which this reply relates, see vol. 83, p. 216.

† See "Hyper-Frequency Wave Guides," *Bell System Technical Journal*.

The design of a negative feed-back amplifier for a frequency range such as 2 megacycles centres around the valve characteristics, as explained on page 589 of the paper. It happened that the valves having the most suitable electrical characteristics even for the earlier stages of the amplifier were "power" valves. New types of valves are now available, and in due course it will be possible to design a repeater with a lower consumption of power. The use of 21 volts (filaments) and 130 volts (anodes) for terminal equipment is in conformity with existing practice at telephone repeater stations, where such equipment will be installed. A higher voltage was necessary for the output stage of the line repeaters. The history attaching to the normal repeater-station voltages would hardly be appropriate in this reply.

The addition of repeaters at intermediate points in the 12-channel system seems likely to prove a practical and economical method of increasing the number of circuits obtainable, but the coaxial case is perhaps less certain. The tolerance of 1·9 miles mentioned in relation to the spacing of coaxial repeater stations is not hard and fast. The upper limit of 7·9 miles, however, is not being exceeded. It is too early yet to say whether the coaxial "phantoms" will be used. The use of a balanced type of high-frequency cable in conjunction with a coaxial submarine link was referred to by Dr. Rosen in the London discussion. In suitable cases the junction could be effected by a transformer or, more frequently, by amplifying equipment.

The figures for change of attenuation, per mile, due to temperature variations, on the New York–Philadelphia coaxial system, are not directly comparable with the London–Birmingham case owing to the higher attenuation per mile of the former, but even so the figures quoted by Mr. Smith are rather surprising.

For information concerning quartz-crystal cutting, reference should be made to a paper on this subject by C. F. Booth and E. J. C. Dixon.* The crystal used to generate the fundamental 400-kc./sec. oscillation is a critically cut crystal of the so-called "zero-temperature coefficient cut." Temperature control was added, at no great cost, to ensure the greatest possible stability.

The gain/frequency curves of negative feed-back repeaters given in the paper are correct within the limitations of the scales used. The surprising evenness of frequency response is one of the remarkable features of this type of amplifier. The term "well designed" was used in the paper, perhaps inadvisedly, in connection with this characteristic. If there is a reduction in gain, due to feed-back, of, say, 15 db. or more, this flatness of characteristic will be in evidence provided the repeater is stable. It is a peculiarity of this type of repeater that it is either all right or all wrong! Provided the design is satisfactory little adjustment is required, though the tracing of design troubles causing instability may be difficult.

The coaxial cable was designed with tubes formed of overlapping Z-shaped ribbons to constitute a self-supporting structure, and no difficulty has been experienced in the transport of the cable when wound on drums of a size appropriate to the diameter of the finished cable. The optimum ratio of conductor diameters, i.e. 3·6, has been adhered to as closely as practicable, though a slight divergence from the optimum ratio in the design is not serious.

A slight divergence from concentricity of the centre wire is of no moment where telephony is concerned; eccentricity needs to be appreciable before increase in attenuation is noticeable. For television, however, it is desirable to approach exact concentricity as far as practicable, as irregularities result in reflections which give rise to interference effects.

The purpose of the thin brass tapes is to hold the components of the tube in position while the thin lead sheath is applied. The lead sheaths on individual tubes are to facilitate subsequent manufacturing operations as well as to reduce cross-talk between tubes and the effect of external disturbances. In the Birmingham–Manchester section of the coaxial cable, thin steel tapes are used instead of the individual lead sheaths, and the brass tapes and thin lead sheaths are not required. The substitution of steel tapes results in a reduction in cost, as well as giving greater immunity from cross-talk and interference. It is not anticipated that there will be any measurable change in the characteristics of the coaxial cable due to any slight oxidization of the internal surface of the tubes and of the centre wire which may occur. In the design of cable, however, in which a thin skin of high-conductivity material, such as a silver plating, might be used to provide the path for the high-frequency currents, any oxidization which took place might have serious effects on the transmission characteristics of the cable. In any case, the characteristics would be directly dependent upon the thickness of the skin of high-conductivity material, and to arrive at a satisfactory practical result would probably require extended trials.

A smaller-diameter coaxial cable, suitable for the transmission of 100 circuits, has been suggested. There would not be any serious practical difficulty in manufacturing such a cable, but for the present it is preferred to confine coaxial systems to routes where larger numbers of circuits are required.

In making joints and terminating the coaxial cable, a sufficient thickness of metal is used to provide for the attenuation of external disturbance effects and cross-talk, but, apart from this, no special precautions have been found necessary owing to the uneven distribution of the high-frequency currents within the thickness of the conducting tubes. Owing to the use of an improved quality of esterified cotton insulation the cable in the Birmingham–Manchester section has lower dielectric losses, and although the tubes are of smaller diameter the attenuation per mile at 2 Mc./sec. will be no greater than that of the London–Birmingham cable.

---

* C. F. Booth and E. J. C. Dixon: "Crystal Oscillators for Radio Transmitters," *Journal I.E.E.*, 1935, vol. 77, p. 197.

As several speakers suggest, the air-space inside the tubes will render ingress of water, in this type of cable, more serious than in normal paper-core cables. With the use of gas pressure, attractive though it is, in the event of the cable being cut the possibility would remain of water running a long way into the cable on a gradient. It has been deemed inadvisable to adopt a gas pressure system, and solid joints have been made to ensure that not more than a single length shall be damaged when the cable has suffered mechanical injury, as by a pick. It is doubtful whether cable could be made fit for use again where ground water has actually entered the tubes. The thin lead sheaths on the tubes cannot be relied upon to keep out water indefinitely, but will be sufficient protection to enable the high-frequency circuits to continue to work in the event of the main cable-sheath being punctured by corrosion or otherwise. Meanwhile, the fall in insulation of the interstice pairs will enable the fault to be localized. The new design of cable with steel tapes will offer less resistance to penetration of the tubes by water, but, even so, tests in the factory have indicated that the fall in insulation in the tubes will be delayed for a considerable time. It appears that breakdown due to the power voltage would probably occur before serious degradation of the high-frequency circuits. The transmission of power over the cable is without effect on its high-frequency characteristics. It was decided to transmit power over the cable to minimize the number of power breakdowns, each of which would paralyse the system unless stand-by generating equipment were provided.

Where the cable passes through areas known to favour corrosion the sheath has been protected with compounded hessian tape. Anti-creepage devices of the normal Post Office design have been provided in one section of the cable.

To facilitate interconnection of 12-channel and coaxial systems it has been decided that, besides the alteration of the channel spacing to 4 kc./sec., the number of channels per group will be increased to 12. It will probably not be economical to branch out less than a super-group at an intermediate point, but such a super-group need not be fully equipped in the first instance.

Screens and earth connections have been freely used on the equipment where experience has suggested their usefulness, notably for the filters and the line repeaters.

The statement that it was impracticable to modulate directly into the megacycle range was not intended to imply that it was impossible. It is largely a matter of economy of design. An impracticably large number of different designs of filters and different carrier frequencies would otherwise be involved.

The great bulk of the equipment for a coaxial terminal is that concerned with assembling the channels into groups, and in consequence every effort was made to simplify and reduce the cost of this equipment. Although the use of cuprous-oxide rectifiers could have been extended to the group modulators, the super-group modulators operate up to frequencies where the capacitances of the rectifiers are so excessive as to prohibit their use completely. The Carson circuit has been used, where valves have been employed, to reduce the number of valves.

Reference has been made to the use of manholes, in America, to house coaxial repeaters. These manholes are, of course, specially constructed for the purpose, but the Post Office has preferred to avoid all risk of flooding by placing the repeaters in small buildings above ground.

The increased number of pairs in the star-quad 12-channel carrier cables has been accompanied by a slight decrease in capacitance per mile as compared with the Bristol–Plymouth twin cable. The actual average capacitances are $0 \cdot 058$ and $0 \cdot 057\,\mu$F per mile, as compared with $0 \cdot 065\,\mu$F for star-quad and multiple-twin cables of normal British construction.

The attenuation of the star-quad carrier cables at 60 kc./sec., however, is somewhat more, owing to greater high-frequency losses resulting from the higher average concentration of copper in the star-quad formation. The increase in the attenuation—from 2·5 db. to 2·6 db. per mile—is too small to warrant a change in the maximum repeater spacing of 22 miles. No difficulties are being experienced with the star-quad cables, and freedom from cross-talk is of similar standard to that obtained in the Bristol–Plymouth scheme.

The reasons which prompted the grading of capacitance in the Bristol–Plymouth system can hardly be satisfactorily explained in this reply, but roughly two purposes were served, namely to obtain a smooth impedance/frequency curve—thus assisting in avoiding reflections from equipment at the ends of repeater sections—and, secondly, to minimize reflections within repeater sections. This latter has a bearing on the use of balancing networks to reduce distant-end cross-talk, as such networks are, in practice, only effective against true distant-end cross-talk and not against cross-talk which has undergone reflections due to irregularities in the impedances of cable-lengths within the repeater section. Incidentally, there appears to have been some misunderstanding concerning the location of the networks. It is not necessary that they should be exactly at the mid-points of repeater sections. At the time the paper was written no decision in the matter had been made, but in future schemes the networks will be at the receiving ends of the cables in each repeater section.

We are unable to agree with the reasoning behind the suggested use of screened pairs as an improvement upon the Bristol–Plymouth cable system. The limitation leading to a repeater spacing of the order of 22 miles resides in the noise that would be introduced by amplifiers on a very long circuit rather than in distant-end cross-talk, and the addition of screens would not affect this limitation. Actually, the 22-mile spacing represents a practical balance between economy in copper and increased expenditure on repeaters and their maintenance, and if it were desired to increase the distance between repeaters the use of heavier conductors would achieve this result in the most straightforward and economical way.

The possibility of reconditioning existing trunk cables for conversion to 12-channel carrier has not been overlooked, but the exceptionally heavy demand for additional circuits on all the main routes has until recently ruled out the release of cables for such work. Progress in the installation of 12-channel schemes in the Scottish region, described by Mr. McKichan, is typical of progress elsewhere in the Post Office system, and pressure has already been relieved to some extent by these new 12-channel cables.

The discussion of the operation of 12-channel systems under fault conditions is of considerable interest. It would not be practicable, even in emergency, to work “ go ” and “ return ” 12-channel systems within a single cable. It is the elimination of near-end cross-talk between “ go ” and “ return ” by using two cables which makes possible the 12-channel system, with its high attenuation between repeaters.

Several speakers ask for information concerning the coplanar-grid valve. An article on this subject will be found in the *Bell System Technical Journal.**

It is true that the distances over which carrier-current working is economical have been continually decreasing, but the use of carrier in subscribers’ cables to avoid laying new cables to provide for growth is surely looking very far ahead.

The question of signalling was not dealt with in the paper because signalling over the circuits on the two systems described is subject only to the same limitations as normal 4-wire trunk circuits, which at present are operated on a generator signalling basis, using a modulated 500-cycle tone. The 2-frequency signalling and dialling system will be of equal value on audio and carrier (12-channel and coaxial) circuits.

---

* H. A. Pidgeon: “Theory of Multi-Electrode Vacuum Tubes,” *Bell System Technical Journal*, 1935, vol. 14, p. 77.

INSTITUTION NOTES

I.E.E. MODEL FORM OF GENERAL CONDITIONS FOR CONTRACTS

Form A of the above Conditions (Home, with Erection), including Forms of Agreement and Guarantee, has been revised. Copies of the new edition (revised 1938) are now available from the Secretary of The Institution, price 2s. (2s. 2d. post free).

THE ENGINEERS’ GERMAN CIRCLE

The following meetings have so far been arranged by the Circle for the coming session and are open to members of The Institution:—

Monday, 7*th November*, at The Institution of Mechanical Engineers, at 6 p.m. (Tea at 5.30 p.m.) Lecture on “ Dampfkesselbau in Deutschland ” (“ Boiler Construction in Germany ”), by Dipl.-Ing. F. Weber, Member of the Executive Committee of the Vereinigung der deutschen Dampfkessel- und Apparate-Industrie E.V.

Monday, 28*th November*, at The Institution of Mechanical Engineers, at 6 p.m. (Tea at 5.30 p.m.) Lecture on “ Die Zerstörungsfreie Werkstoffprüfung in Deutschland ” (Non-destructive Testing in Germany), by Dr. R. Berthold, of the Reichs-Röntgenstelle beim Staatl Material-prüfungsamt, Berlin.

Members can join the Circle by paying an annual subscription of 7s. 6d. The Honorary Secretary is Mr. E. L. Diamond, M.Sc.(Eng.), c/o The Institution of Mechanical Engineers, Storey’s Gate, St. James’s Park, S.W.1.

TRANSFERS

The following transfers were effected by the Council at their meeting held on the 30th June, 1938:—

Student to Graduate

Anderson, Murice Hector.
Bailey, John Claude.
Balchin, Douglas Bernard, B.Sc.(Eng.).
Dennis, Harry Pollard.
Dey, Douglas G.
Douglas, Cecil Stuart, B.Sc.(Eng.)
Falk, Alan David.
Fuller, Alec Henry.
Holman, John Arthur, B.Sc.(Eng.).
Leitch, Donald Dewar, B.Sc.
Liebert, Frank Peter, B.Sc. Tech.
McTaggart, Michael Aloysius.
Majumdar, Denoy Kumar.
Mills, Cyril Jack.
Morris, John Francis, B.Sc. (Eng.).
Nicholas, Walter Archibald.
Oliver, Noel, B.Sc.Tech.
Pereira-Mendoza, Vivian Moses, B.Sc.Tech.
Payne, Thomas Carruthers, B.Sc.
Porter, Harold.
Purves, Ronald Marshall.
Robinson, Allen Charles.
Ross, John Prentice, B.Sc.
Russell, Graham, B.Sc.
Schäffer, Paul, B.Sc.
Scorgie, Guy Craig, B.Sc.
Scott-Lindsley, Mervyn Ewart.
Searle, Kenneth Arthur, B.Sc.(Eng.).
Smith, Bernard James.
Tuttiett, Laurence Anthony.
Walsh, Maurice Edward, B.Sc.(Eng.).
Warburton-Gray, Stanley Gordon F.
Wasal, Niranjan Singh.

ACCESSIONS TO THE REFERENCE LIBRARY

[Note.—The books cannot be purchased at The Institution; the names of the publishers and the prices are given only for the convenience of members; (*) denotes that the book is also in the Lending Library.]

Academy of Motion Picture Arts and Sciences. Motion picture sound engineering. A series of lectures. 8vo. xx + 553 pp. (New York: D. Van Nostrand Co., Inc., 1938.) 20*s*. (*)

Alber, E. Automobile electrical repairs. sm. 8vo. vii + 108 pp. (London: E. and F. N. Spon, Ltd., 1938.) 3*s*. 6*d*. (*)

Andersen, R. C., *M.C.*, and Dannenberg, K. New fuse efficiency and economy manual. 8vo. 56pp. (London: Electric Transmission Ltd., 1937.)

Barrows, W. E. Light, photometry and illuminating engineering. 2nd ed. 8vo. x + 445 pp. (New York; London: McGraw-Hill Book Co., Inc., 1938.) 24*s*. (*)

Beaumont, W., *M.R.C.S.*, *L.R.C.P.* Infra-red irradiation. With a foreword by Lord Horder. sm.8vo ix + 139 pp. (London: H. K. Lewis and Co., Ltd. 1936.) 6*s*. 6*d*.

Bell, E. T., *Ph.D.* Men of mathematics. 8vo. 653 pp. (London: Victor Gollancz, Ltd., 1937.) 12*s*. 6*d*. (*)

Binder, L., *Dr.-Ing.* Die Wanderwellenvorgänge auf experimenteller Grundlage. Aus Anlass der Jahrhundertfeier der Technischen Hochschule Dresden . . . dargestellt von L. B. (Berlin: Julius Springer, 1928.) *RM*. 23.50.

Bitter, F. Introduction to ferromagnetism. 8vo. xi + 314 pp. (New York, London: McGraw-Hill Book Co., Inc., 1937.) 24*s*.

Bolton, D. J., *M.Sc.* Costs and tariffs in electricity supply. 8vo. xii + 214 pp. (London: Chapman and Hall, Ltd., 1938.) 12*s*. 6*d*. (*)

Burstyn, W., *Dr.* Elektrische Kontakte. Grundlagen für den Praktiker. 8vo. vi + 79 pp. (Berlin: Julius Springer, 1937.) *RM*. 6.60.

Cameron, J. R. Sound motion pictures: recording and reproducing. 8vo. 310 pp. (Cameron Publishing Co., Woodmont, Conn., U.S.A., 1937.) 30*s*. (*)

Campbell, G. A. The collected papers of George Ashley Campbell, research engineer of the American Telephone and Telegraph Company. la. 8vo. xii + 548 pp. (New York: American Telephone and Telegraph Company, 1937.)

Cartwright, A. B. The drawing office handbook. 2nd ed. 8vo. 27 pp. (London: The Drawing Office Material Manufacturers' and Dealers' Association, 1936.) 5*s*. (*)

Christie, V. B., *M.A.* Electrical engineering. The theory and characteristics of electrical circuits and machinery. 5th ed. 8vo. xxii + 717 pp. (New York: McGraw-Hill Publishing Co., Ltd., 1938.) 30*s*. (*)

Clark, C. H. D., *D.Sc.* The fine structure of matter. pt. 2, Molecular polarization. Being vol. 2 of "A comprehensive treatise of atomic and molecular structure." 8vo. lxxii + 217–457 pp. (London: Chapman and Hall, Ltd., 1938.) 15*s*. (*)

Commission Internationale de l'Éclairage. 9e session, Berlin et Karlsruhe—juillet 1935. Recueil des travaux et compte rendu des séances. 8vo. vii + 679 pp. (Cambridge: University Press, 1937.) 20*s*.

Conférence Internationale des Grands Réseaux Électriques à Haute Tension. Compte-rendu des travaux de la 9e session, 24 juin–3 juillet, 1937. Etabli par J. Tribot-Laspière. 3 tom. 8vo. Paris, Avenue Marceau, 54: Conférence Internationale des Grands Réseaux Électriques, 1938.) 450 *francs*.

Copper Development Association. Publication no. 29: Copper in cast steel and iron. 8vo. 136 pp. (London: Copper Development Association, 1937.)

Cotton, H., *M.B.E.*, *D.Sc.* Electrical technology. A textbook for the following examinations: National Certificate, City and Guilds, I.E.E., B.Sc. Engineering. 3rd ed. 8vo. xiv + 523 pp. (London: Sir Isaac Pitman and Sons, Ltd., 1938.) 12*s*. 6*d*. (*)

Croft, T. Central stations. 3rd ed., revised by G. H. Hall. 8vo. xii + 360 pp. (New York, London: McGraw-Hill Book Co., Inc., 1937.) 18*s*. (*)

Croft, T. Electrical machinery. Principles, operation, and management. 4th ed., revised by G. H. Hall. 8vo. xii + 394 pp. (New York; London: McGraw-Hill Publishing Co., Ltd., 1938.) 18*s*. (*)

Cross, H. H. U. The battery book. A practical manual on the construction, charging, care and repair of automobile, motor cycle, radio, aviation, electric vehicle, medical and other similar batteries. With a foreword by J. Y. Fletcher. sm. 8vo. xii + 196 pp. (London: The Technical Press, Ltd., 1937.) 5*s*. (*)

Déribéré, M. La régulation automatique des fours électriques. Préface de A. Levasseur. 8vo. vi + 87 pp. (Paris: Dunod, 1938.) 25 *francs*.

Eccles, H. Glass working for luminous tubes. sm. 8vo. 143 pp. (London: Blandford Press Ltd., 1937.) 5s.

Einstein, A., *Ph.D.*, and Infeld, L. The evolution of physics: the growth of ideas from the early concepts to relativity and quanta. 8vo. x+319 pp. (Cambridge: University Press, 1938.) 8*s*. 6*d*. (*)

Elliott, W. F. Sound-recording for films. A review of modern methods. With a foreward by P. Rotha. 8vo. xi + 134 pp. (London: Sir Isaac Pitman and Sons, Ltd., 1937.) 10*s*. 6*d*. (*)

Engineers' Who's Who, 1937. Compiled and edited by M. E. Day. 183 pp. (London: The D.M.A. Co., Ltd., 1937.) 20*s*.

Feldtkeller, R., *Dr.* Einführung in die Vierpoltheorie der elektrischen Nachrichtentechnik. (Physik und Technik der Gegenwart; herausgegeben von H. Fassbender, Band 2.) 8vo. ix + 142 pp. (Leipzig: S. Hirzel, 1937.) *RM*. 10.

Field, S., and Weill, A. D. Electro-plating. A survey of modern practice, including nickel, zinc, cadmium, chromium, and the analysis of solutions. 3rd ed. sm. 8vo. x + 381 pp. (London: Sir Isaac Pitman and Sons, Ltd., 1938.) 12*s*. 6*d*. (*)

Fink, D. G. Engineering electronics. 8vo. xiii + 358 pp. (New York; London: McGraw-Hill Publishing Co., Ltd., 1938.) 21*s*. (*)

Fleming, *Sir* J. A., *M.A.*, *D.Sc.*, *F.R.S.* Elementary mathematics for electrical engineers. 8vo. 110 pp. (London: George Newnes, Ltd., 1938.) 5*s*. (*)

£120 SAVED PER ANNUM
TYPE A.P.F. WITH COVER REMOVED

A manufacturer is saving £123 . 5 . 8 per annum by using a Dubilier condenser. His original tariff, a graded scale, averaged 1d. per unit. By improving the power factor with a Dubilier Power Factor Correction Condenser from ·87 to ·95 he was able to transfer to a much more advantageous tariff, which averaged ·85d. per unit for the first 26,250 units per quarter and ·75d. per unit for the balance. His annual consumption is 162,350 units and his account has now been reduced from £676 . 9 . 2 to £553 . 3 . 6. As this saving cannot be effected without great reliability, a Dubilier Power Factor Correction Condenser, which has no moving parts, is installed, assuring him of many years of trouble-free service.

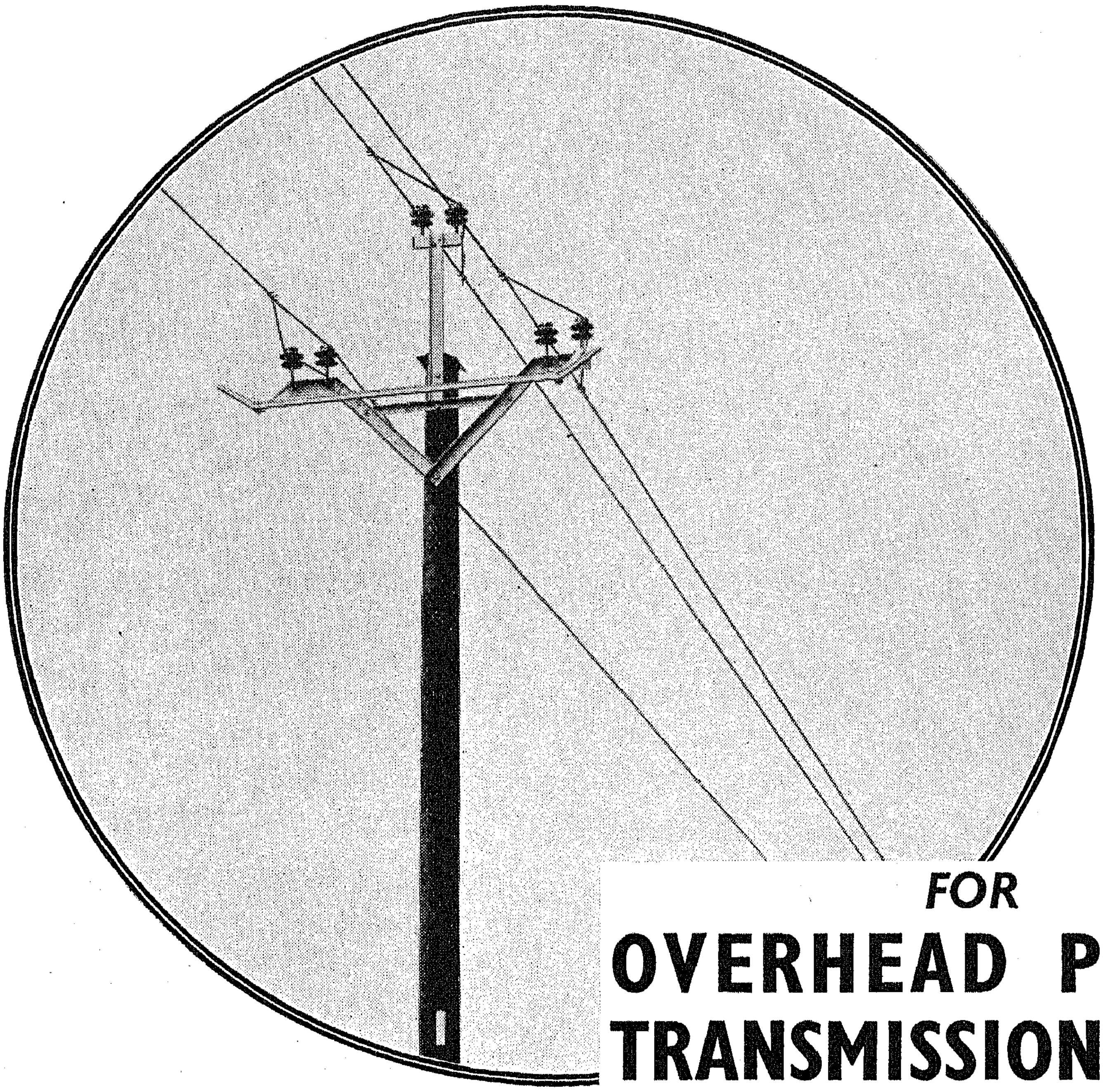
Reliability is of greater importance than first cost, and in the long run it is more economical to buy Dubilier Power Factor Correction Condensers.

DUBILIER

POWER FACTOR CONDENSERS

DUBILIER CONDENSER CO. (1925) LTD., DUCON WORKS, VICTORIA ROAD, NORTH ACTON, LONDON, W.3

C. R. Casson, P.F.7



We also supply Cadmium Copper Trolley Wire to B. S. S. 23—1933.
and
Cadmium Copper Line Wire for Telephone & Telegraph purposes to B. S. S. 175—1927.

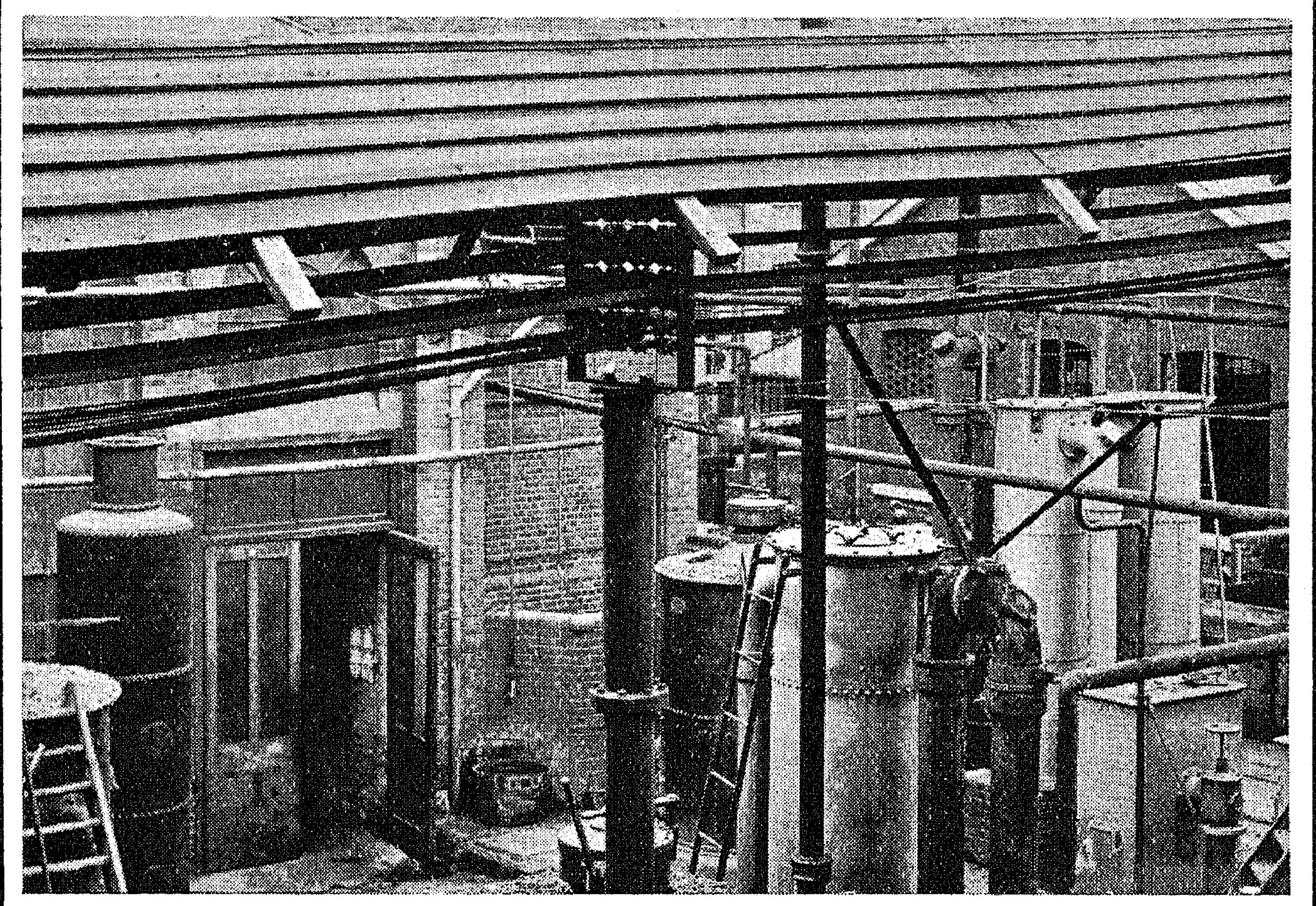
FOR
OVERHEAD POWER TRANSMISSION LINES

No other non-ferrous material combines electrical and mechanical advantages for high tensile overhead line conductors so effectively as B.I. CADMIUM COPPER. Hard drawn wires containing approximately 1% cadmium, have 30% to 50% greater tensile strength than hard drawn copper wires of equal section ; and an electrical conductivity not less than 83% of the I.E.C. Standard for annealed copper.
The high conductivity of B.I. CADMIUM COPPER wire as compared with other high tensile conductors enables smaller wire to be used with reduced ice and wind loading. The cost of supporting structures may be thereby reduced, while the high tensile strength allows of longer spans.
Other advantages of B.I. CADMIUM COPPER are its high fatigue strength and its resistance to atmospheric corrosion. It complies with the requirements of British Standard Specification No. 672—1936.
We have ample facilities for the production of Cadmium Copper and have supplied it extensively during the past 15 years.

B.I. CADMIUM COPPER

BRITISH INSULATED CABLES LTD., PRESCOT, LANCS.
Tel. No. Prescot 6571. *London Office*, Surrey House, Embankment, W.C. 2. Tel. No. Temple Bar 7722

WE PUBLISHED THIS PICTURE IN 1910



ALUMINIUM CONDUCTORS
OVER A GAS-PRODUCING PLANT

A recent rearrangement of the works at Messrs. Hoffmann Manufacturing Co. Ltd., Chelmsford, has necessitated the removal of the aluminium conductors which were found in perfect condition after 28 years' efficient service.
Specimens can be seen at any time at our Head Office in Adelaide House.

EMPIRE
EXHIBITION
SCOTLAND 1938

PALACE
OF
ENGINEERING

STANDS
E.38 & E.128

THE

British Aluminium

CO. LTD.

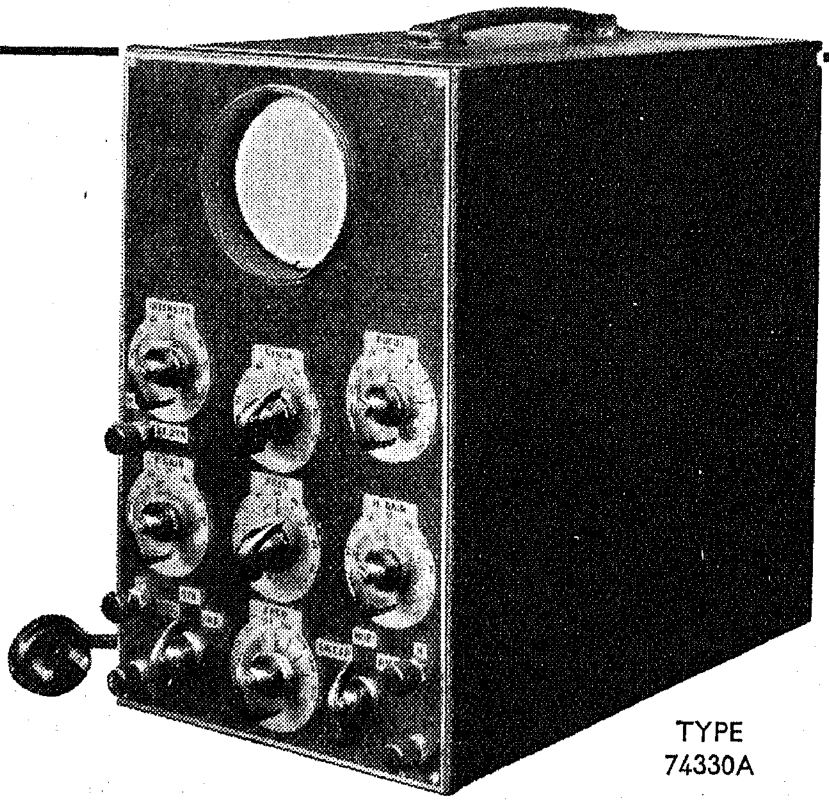
HEAD OFFICE: ADELAIDE HOUSE, LONDON, E.C.4. Telephone: Mansion House 5561. Telegrams: "Cryolite, Bilgate, London."

A Portable

OSCILLOGRAPH

incorporating

HIGH VACUUM CATHODE RAY TUBE



TYPE
74330A

AN inexpensive universal instrument for HIGH or LOW FREQUENCY WORK.

- **Incorporates a new High Vacuum Tube with 3″ diameter screen**
- **Horizontal and Vertical Amplifiers.**
- **Linear Time Base which is balanced to insure uniformly good focus over the whole screen.**
- **Operates from A.C. Mains, is compact and easily portable.**

PRICE IN GREAT BRITAIN AND N. IRELAND - £17 . 10 . 0

ILLUSTRATED LITERATURE WILL BE SUPPLIED UPON REQUEST

Standard Telephones and Cables Limited

NORTH WOOLWICH LONDON . E. 16

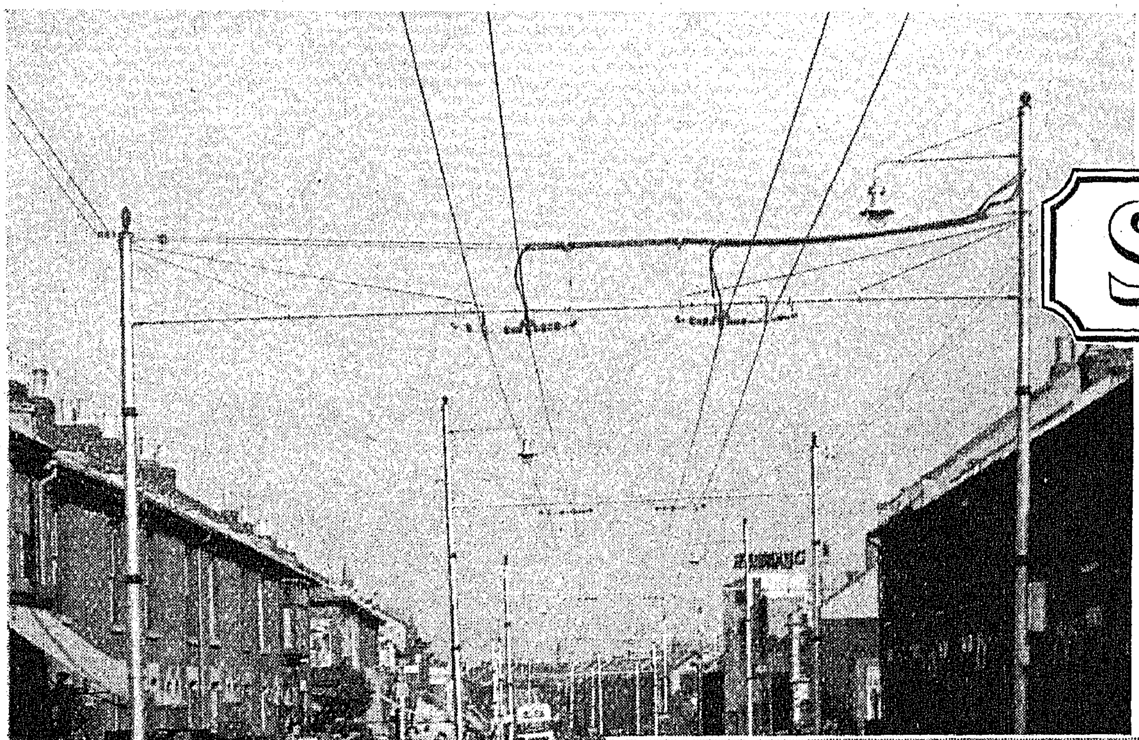
Telephone Albert Dock 1401

Research never ceases

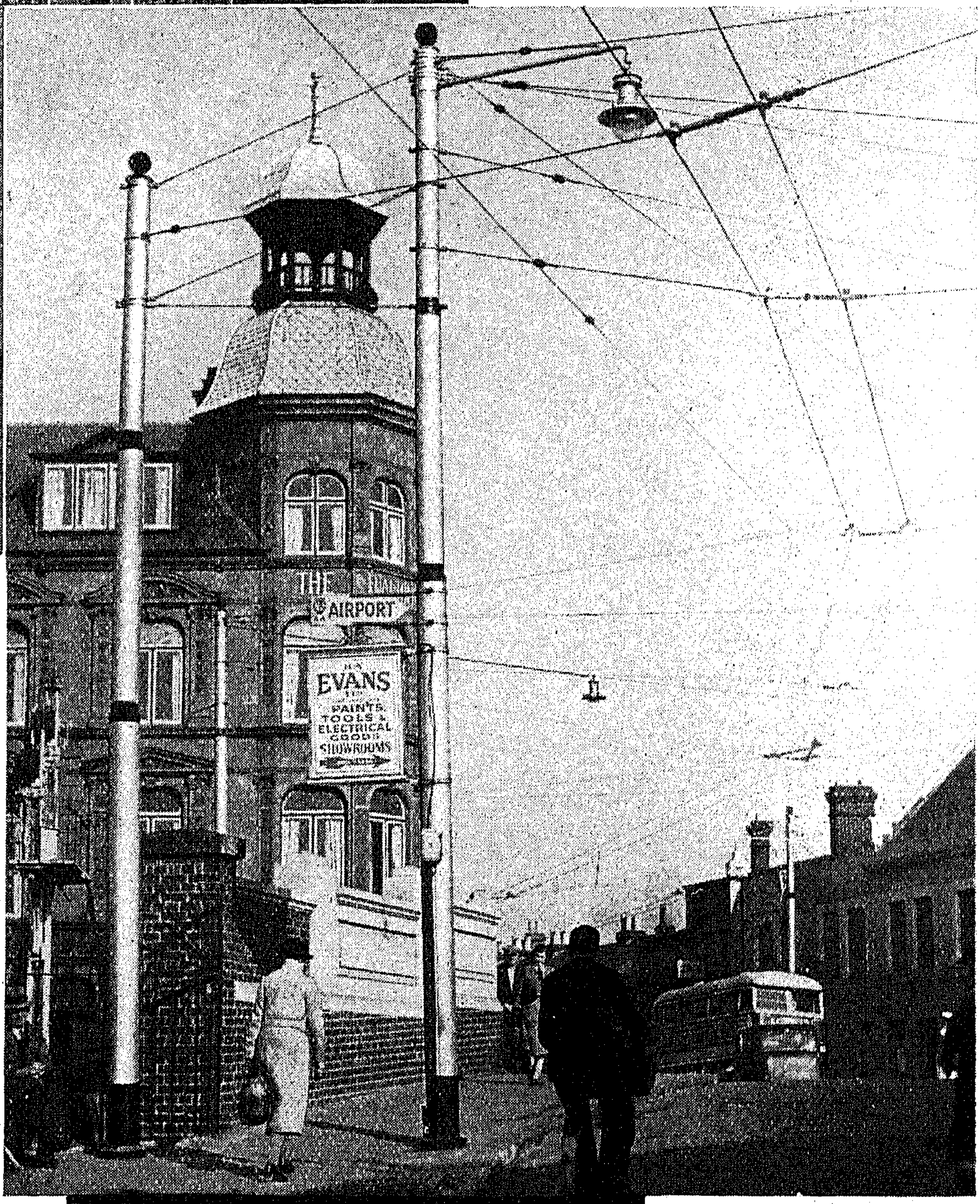
Believing nothing is so good that it cannot be better, we have a large staff of research workers constantly seeking ways and means of improving the Ferranti Meter.

FERRANTI
METERS

FERRANTI LTD., HOLLINWOOD, LANCS. *London Office:* Bush House, Aldwych, W.C.2.



S&L



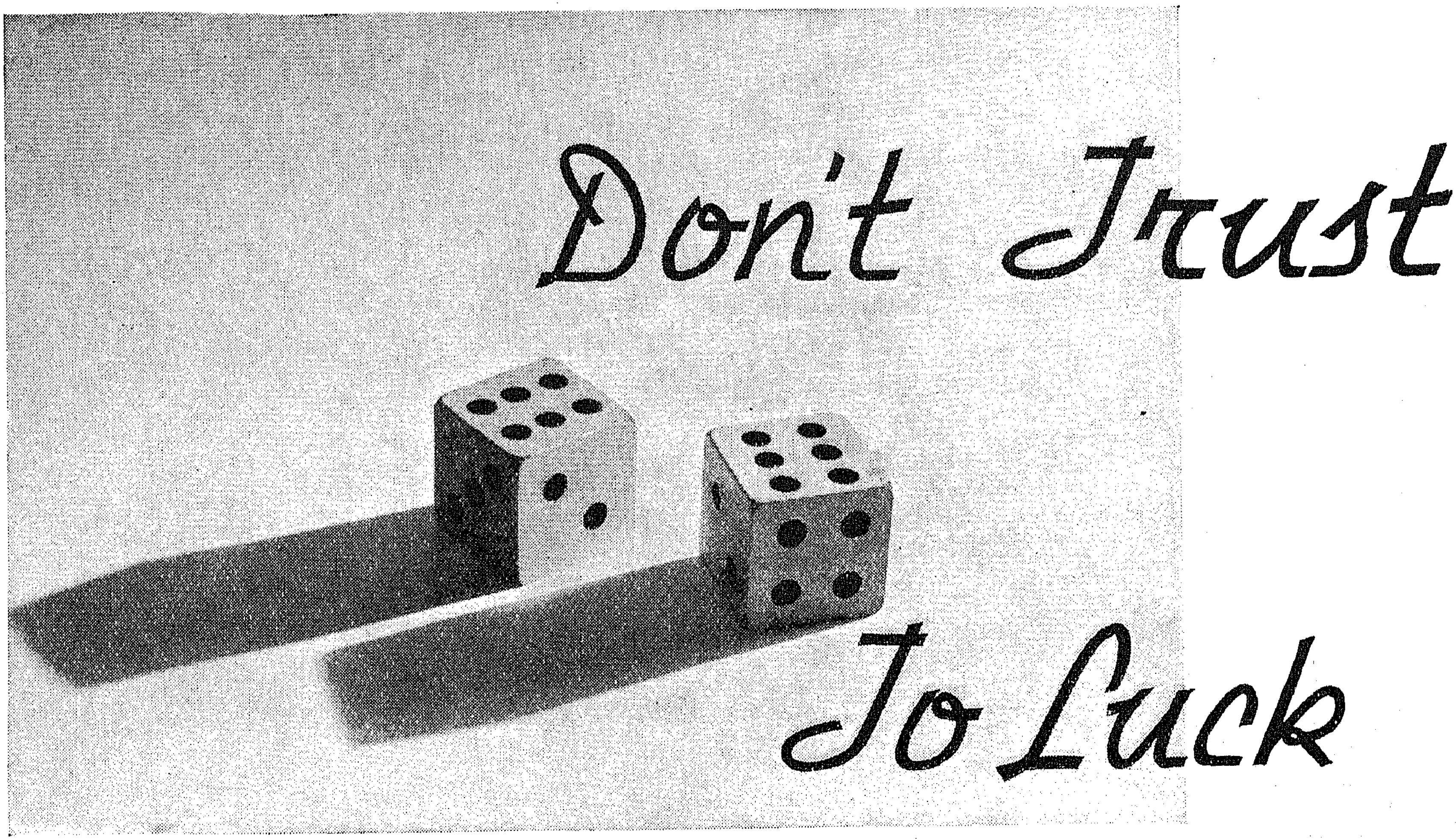
Stewarts and Lloyds' tubular steel poles are being used to an ever-increasing extent for trolley-bus poles and electric and gas lighting poles. They are immensely strong and being ductile—not brittle—resist impact in the event of accident.

In the top view note the tubular cross bracing carrying trolley-bus overhead wires. In the bottom view the braced pole in the foreground stands at a six-way junction, where, we are told, it carries the heaviest suspended gear in the country, the total weight being some 3½ tons.

The use of 'S & L' steel poles is a distinct contribution to public safety because of their strength, their freedom from breakage, and their adaptability to the most varied and onerous conditions.

STEWARTS AND LLOYDS, LTD.

GLASGOW BIRMINGHAM LONDON



Use a rectifier that has behind it a proved record of ten years' outstanding reliability and efficiency. A rectifier that will give satisfactory service for years and years without any attention or renewal. A Westinghouse British-made Copper-oxide Metal Rectifier.

• Westinghouse
British - made
Copper-oxide

METAL RECTIFIERS

can be depended upon - always

Write for booklet D.P.11/I.E.E.

Westinghouse Brake & Signal Co. Ltd., 82, York Way, King's Cross, London, N.1.

THE SMITH TYPE A.P.F PREPAYMENT METER WITH FIXED CHARGE COLLECTOR

Comprehensive...yet how SIMPLE

COLLECTION OF ARREARS

The mechanism used in the Smith Two-Part Tariff Prepayment Meter, Type "A.P.F." for the collection of arrears in the fixed charge is one of the most outstanding inventions in meter design that has been achieved in recent years. It provides the greatest convenience and consideration for the consumer and the supply company.

THE KEYNOTE OF THE MECHANISM IS SIMPLICITY.

Whenever the consumer falls into arrears with the fixed charge the power from the synchronous motor is automatically transferred to a spring which is wound up in proportion to the amount of the arrears. By a simple setting the effects of the synchronous motor and the unwinding of the spring become additive and the consumer is enabled to pay off the accumulated arrears at the same rate per week as the fixed charge, the rate per unit remaining unaltered.

SMITH METERS

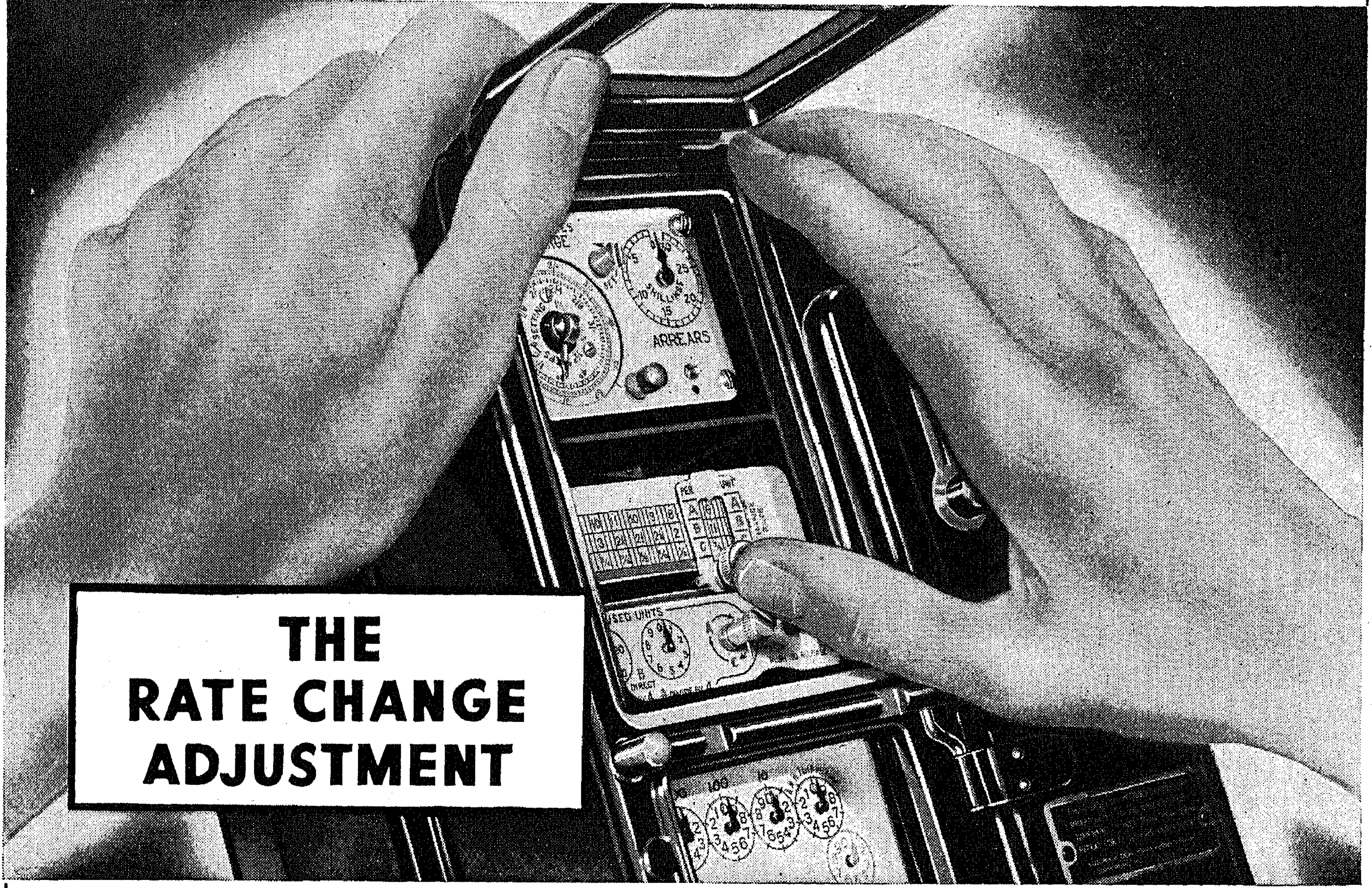
SMITH METERS LTD., ROWAN RD., STREATHAM VALE, S.W.16. POLLARDS 2271

Manufactured under Smith and Angold Patents

INHERENT ACCURACY

THE SMITH TYPE A.P.F. PREPAYMENT METER WITH FIXED CHARGE COLLECTOR

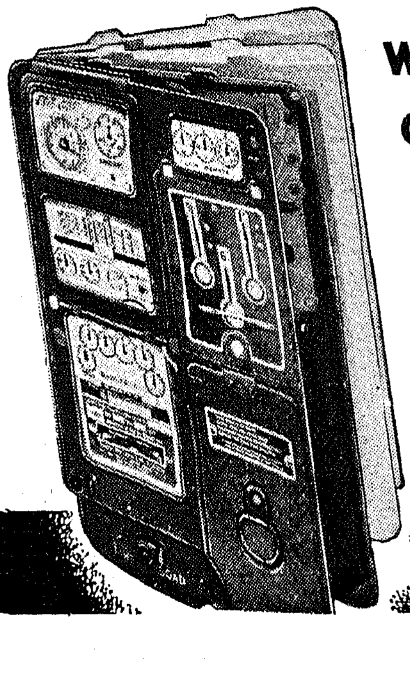
COMPREHENSIVE... YET HOW SIMPLE



THE
RATE CHANGE
ADJUSTMENT

Accuracy and simplicity in adjustment are the outstanding features in the rate-change mechanism unit in the Smith Type 'A.P.F.' Prepayment Meter. Three scales, with a convenient slider, provide 108 possible rates between ¼d. and 1s. 4d. per unit.

As we have stated already, this easy price change with the Fixed Charge Collector completes the provision for conversion of "straight" Prepayment Meters to Two-Part Tariff Prepayment Meters.

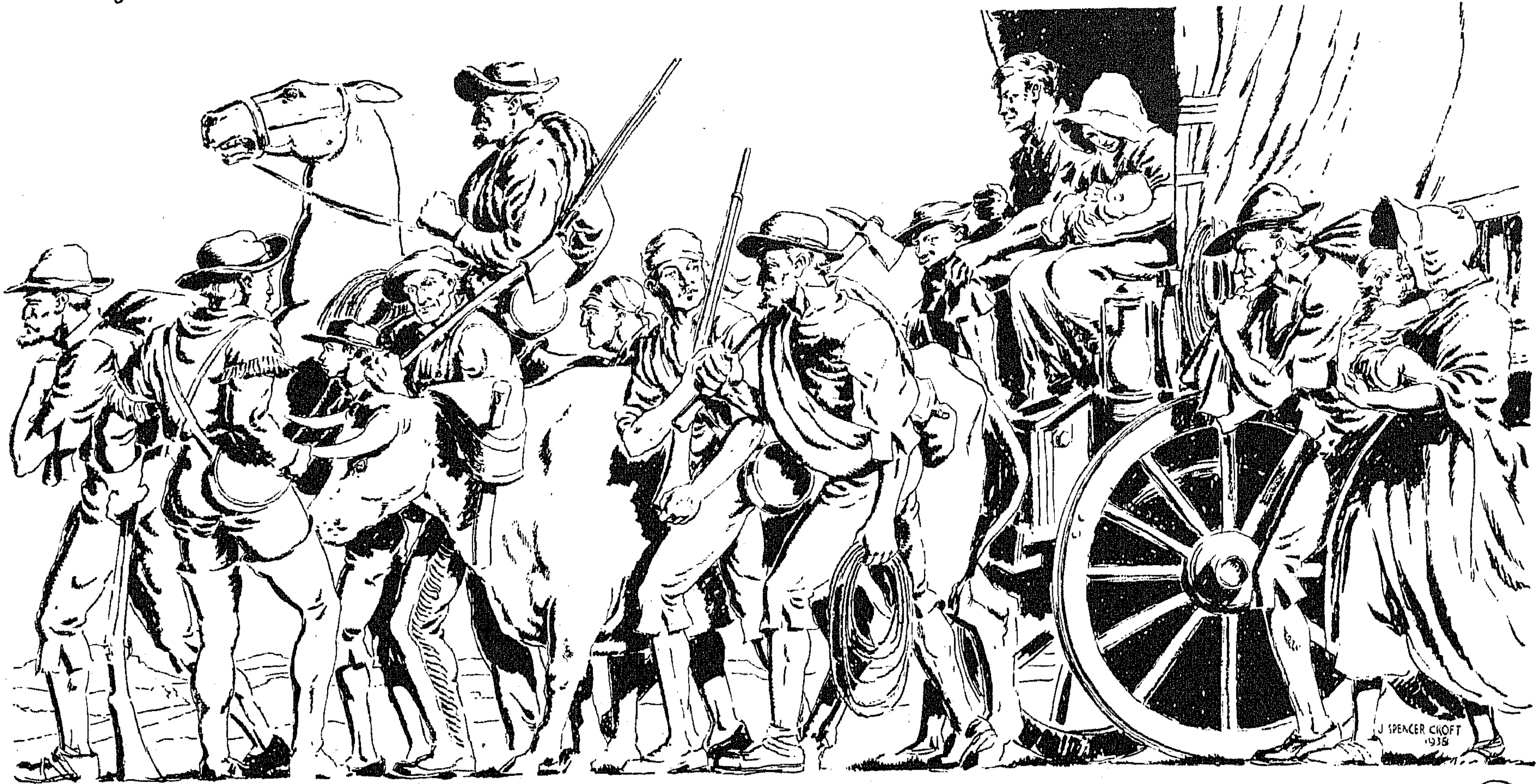


WHAT COULD BE SIMPLER, MORE EFFECTIVE, CONVENIENT, OR ACCURATE — OR MORE COMPREHENSIVE!

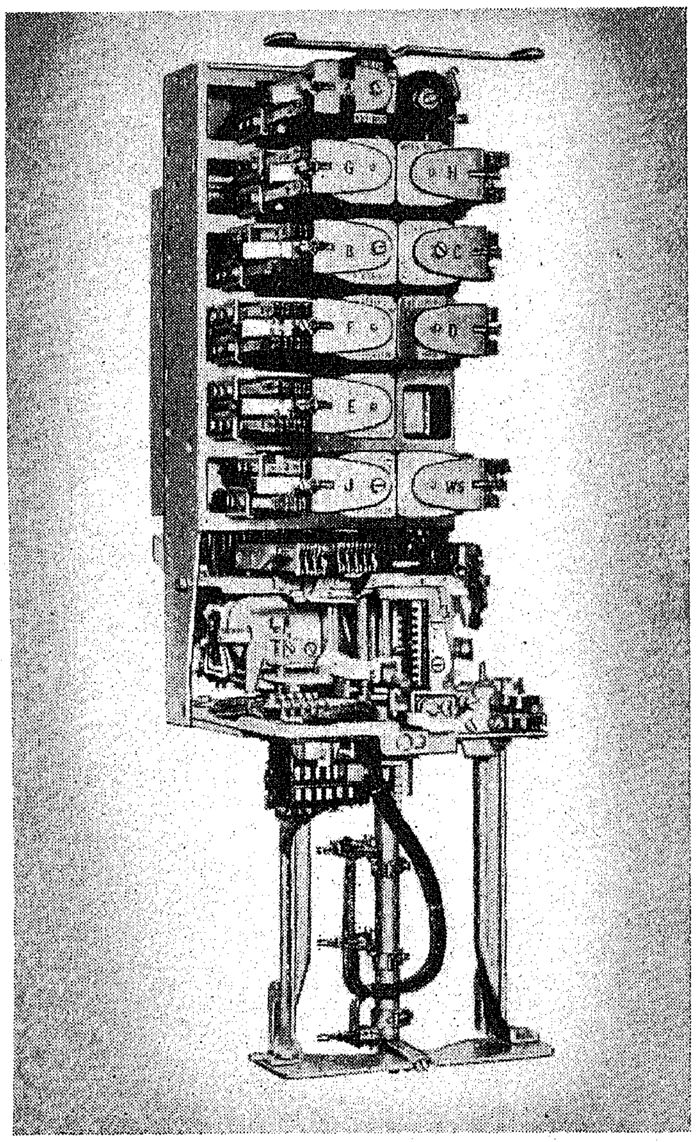
SMITH METERS

SMITH METERS LTD., ROWAN RD., STREATHAM VALE S.W.16. POLLARDS 2271
Manufactured under Smith and Angold Patents

INHERENT ACCURACY



THEY BUILDED BETTER THAN THEY KNEW



The Strowger 32A 200 lines Final Selector.

SOME forty years ago the pioneers of the Strowger system of automatic telephony produced their first switching mechanism for the automatic connection of subscribers. It operated upon the decimal principle and it appeared to its originators to be fundamentally sound, although naturally capable of improvement as automatic telephony developed.

Just how sound the principle was is evidenced by the introduction into service of the new type 32A Selector, for this mechanism, which may without exaggeration be described as one of the most important contributions yet made to automatic telephone switching methods, operates upon the same decimal basis of subscriber selection first enunciated forty years ago. This retention of the original principle was by no means regarded as essential when the technicians at Strowger Works commenced their efforts in 1930, to produce a mechanism which would be superior both in operating characteristics and in construction to the highly efficient Strowger Selectors already in service. Those concerned were so bent upon achieving their end that they were prepared to abandon the principle which had proved so successful in the past and to embark upon a new system of operation if one could be found which was definitely superior from every viewpoint.

But their early investigation and the intensive research and exhaustive tests which followed only served to prove that the Strowger principle of decimal working coupled with a selector operating upon the two-motion principle is unsurpassed by any other. Two triumphs are thus typified in the new 32A Strowger Selector. It represents the continued superiority of a forty years' old principle and the successful culmination to six years of research and development.

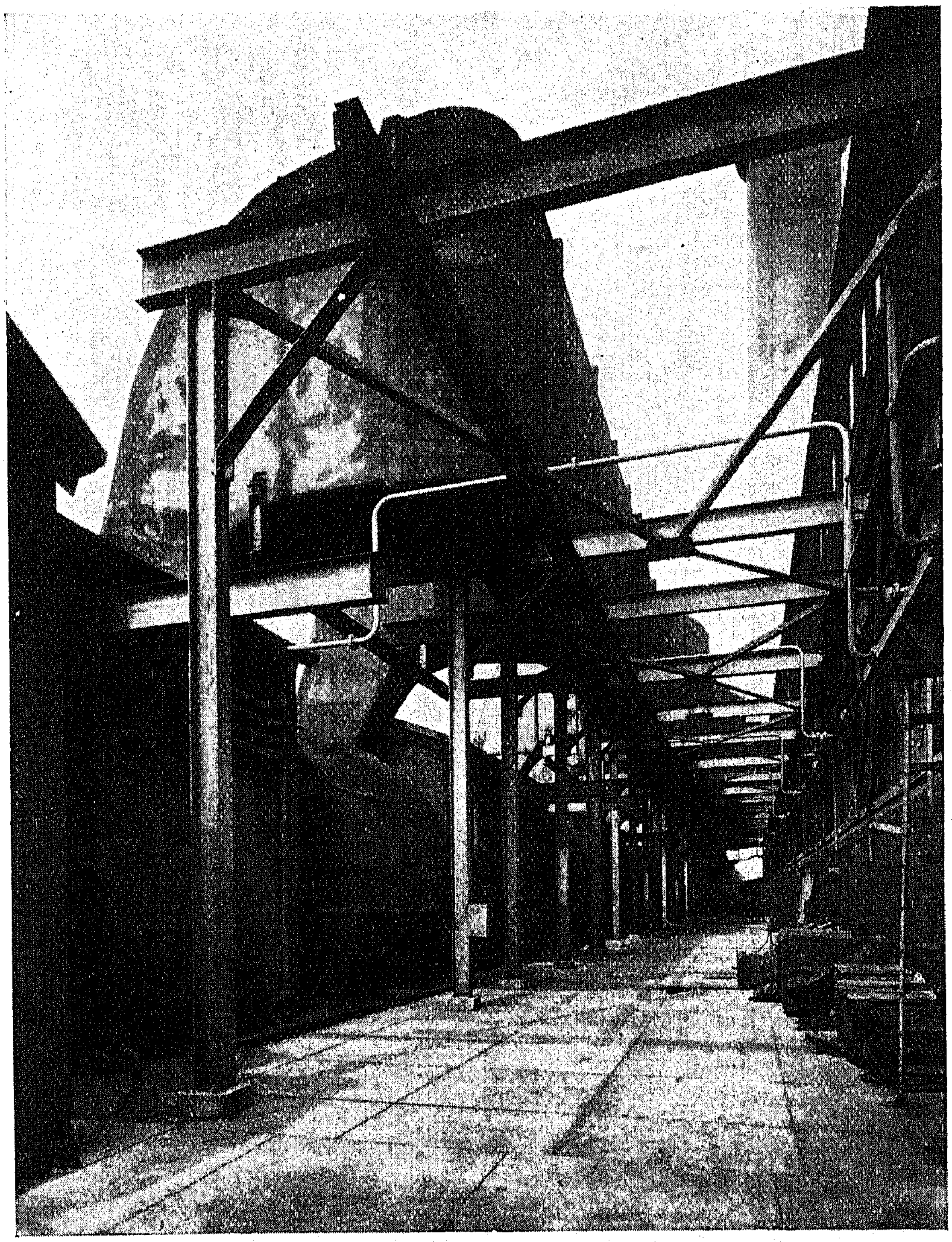
AUTOMATIC TELEPHONE & ELECTRIC CO. LTD.

MELBOURNE HOUSE, ALDWYCH, LONDON, W.C.2 'Phone Temple Bar 4506 'Grams "Strowger, Estrand, London"
Export Sales: NORFOLK HOUSE, NORFOLK ST., STRAND, W.C.2 'Phone Temple Bar 9262 'Grams "Autelco, Estrand, London"
STROWGER WORKS, LIVERPOOL, 7 'Phone Old Swan 830 'Grams "Strowger, Liverpool"

TRADE SIROCCO MARK

PRODUCTS

Mechanical Draft Plant



Part of the Mechanical Draft Installation—servicing four Boiler Plants.

" SIROCCO " induced Draft Fans and "DAVIDSON" Patent Centrifugal Flue Dust Collectors at Clarence Dock Power Station (Corporation of Liverpool Electricity Department) *P. J. Robinson, M.Eng., M.I.Mech.E., M.I.E.E., City Electrical Engineer.*

Ask for new Publication, Ref. No. SF66, describing " DAVIDSON " patent Flue Dust Collectors. *(New Mechanical Draft Publication now in course of preparation.)*

Use " SIROCCO " Air Conditioning for personal comfort and specialised process manufacture.

¶ **"SIROCCO" Mechanical Draft is at work in the majority of Power Stations selected for *National* Electricity Supply.**

Manufactured by

Davidson & Co. Ltd., *Sirocco Engineering Works,* Belfast

LONDON - MANCHESTER - GLASGOW - BIRMINGHAM - NEWCASTLE - CARDIFF - BRISTOL - DUBLIN

CABLES

WITH INSURANCE

C.M.A. Cables by reason of their quality, offer a complete assurance of reliability and dependable service . . .

. . . that's why it pays to specify and use cables made by members of the C.M.A.

C.M.A.

C.M.A. *Regd. Trade Mark Nos.* 422219-20-21
NONAZO *Regd. Trade Mark No.* 458865

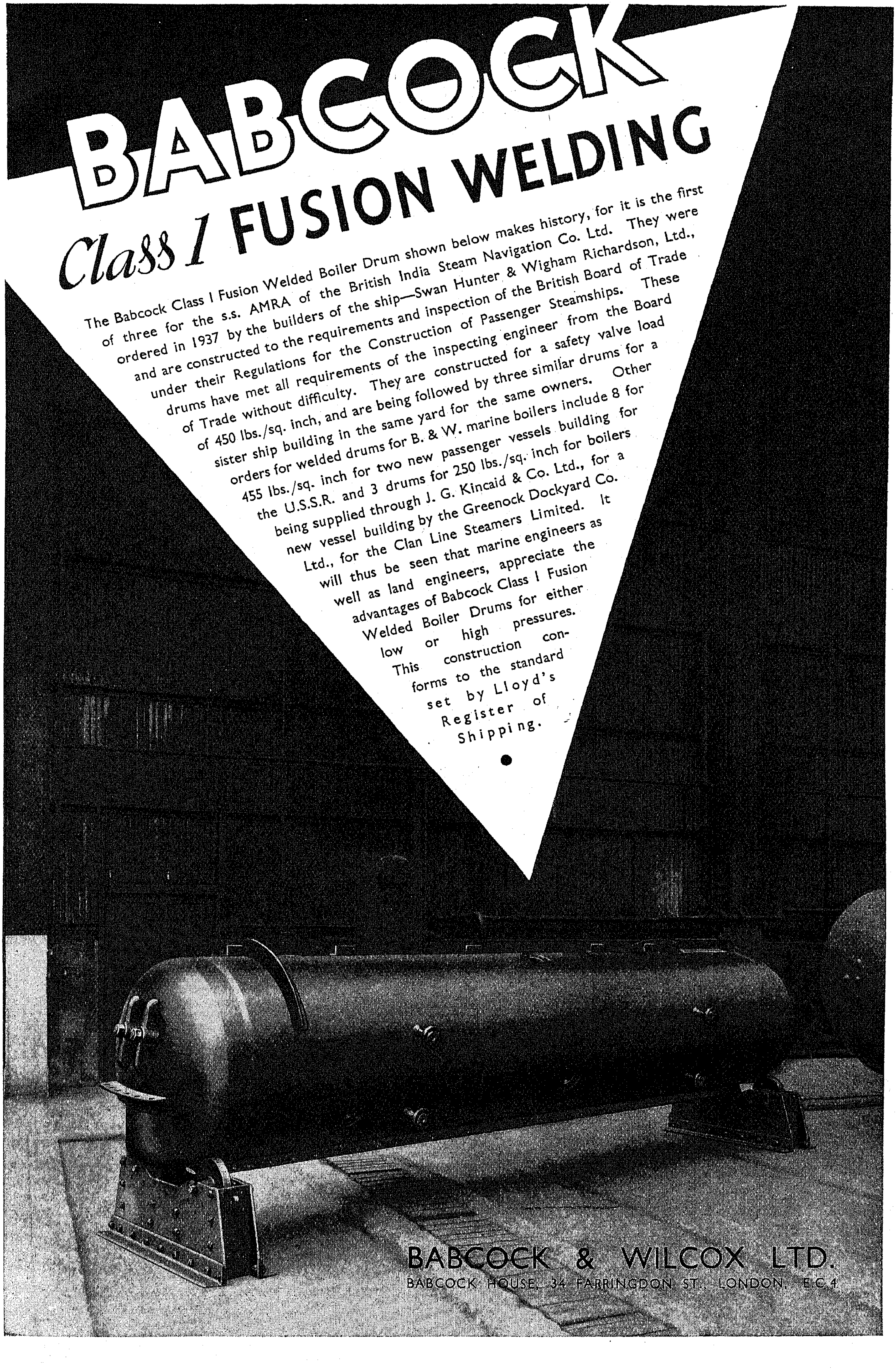
CABLES

MEMBERS OF THE C.M.A.

- The Anchor Cable Co. Ltd.
- British Insulated Cables Ltd.
- Callender's Cable & Construction Co. Ltd.
- The Craigpark Electric Cable Co. Ltd.
- Crompton Parkinson Ltd. (Derby Cables Ltd.)
- The Enfield Cable Works Ltd.
- Edison Swan Cables Ltd.
- W. T. Glover & Co. Ltd.
- Greengate & Irwell Rubber Co. Ltd.
- W. T. Henley's Telegraph Works Co. Ltd.
- The India Rubber, Gutta-Percha & Telegraph Works Co. Ltd. (The Silvertown Co.)
- Johnson & Phillips Ltd.
- Liverpool Electric Cable Co. Ltd.
- The London Electric Wire Co. & Smiths Ltd.
- The Macintosh Cable Co. Ltd.
- The Metropolitan Electric Cable & Construction Co. Ltd.
- Pirelli-General Cable Works Ltd. (General Electric Co. Ltd.)
- St. Helens Cable & Rubber Co. Ltd.
- Siemens Brothers & Co. Ltd. (Siemens Electric Lamps & Supplies Ltd.)
- Standard Telephones & Cables Ltd.
- Union Cable Co. Ltd.

Copyright Colonel Sir Thomas F. Purves
Exclusive Licensees Members of the C.M.A.

Advt. of the Cable Makers' Association, High Holborn House, 52-54, High Holborn, W.C.1. Phone: ***Holborn 7633***



BABCOCK

Class I FUSION WELDING

The Babcock Class I Fusion Welded Boiler Drum shown below makes history, for it is the first of three for the s.s. AMRA of the British India Steam Navigation Co. Ltd. They were ordered in 1937 by the builders of the ship—Swan Hunter & Wigham Richardson, Ltd., and are constructed to the requirements and inspection of the British Board of Trade under their Regulations for the Construction of Passenger Steamships. These drums have met all requirements of the inspecting engineer from the Board of Trade without difficulty. They are constructed for a safety valve load of 450 lbs./sq. inch, and are being followed by three similar drums for a sister ship building in the same yard for the same owners. Other orders for welded drums for B. & W. marine boilers include 8 for 455 lbs./sq. inch for two new passenger vessels building for the U.S.S.R. and 3 drums for 250 lbs./sq. inch for boilers being supplied through J. G. Kincaid & Co. Ltd., for a new vessel building by the Greenock Dockyard Co. Ltd., for the Clan Line Steamers Limited. It will thus be seen that marine engineers as well as land engineers, appreciate the advantages of Babcock Class I Fusion Welded Boiler Drums for either low or high pressures. This construction conforms to the standard set by Lloyd's Register of Shipping.

●

BABCOCK & WILCOX LTD.
BABCOCK HOUSE, 34 FARRINGDON ST. LONDON, E.C.4

ZENITH

(Regd. Trade-Mark)

ELECTRICITY SUPPLY (METERS) ACT, 1936

Three-phase Control Equipment.
0·05-100 Amperes, 0-500 Volts.

CURRENT, POTENTIAL and POWER FACTOR CONTROL APPARATUS

for METER TESTING

Equipment supplied to meet all requirements, and to comply in all respects with the provisions of the above Act.

Complete sets, or components, including Current and Potential Transformers, Rheostats, Resistances, Control Gear, Phase-Shifting and Regulating Transformers, Meter Benches, etc.

Quotations and suggestions gladly forwarded on request.

The ZENITH ELECTRIC CO. Ltd.

Contractors to H.M. Admiralty, War Office, Air Ministry, Post Office, Principal Electricity Undertakings, etc.

ZENITH WORKS, VILLIERS ROAD
WILLESDEN GREEN, LONDON, N.W.2

Telephone: WILlesden 4087-8-9
Telegrams: "Voltaohm, Phone, London"

The ANSWER to every Electrical Test

BRITISH MADE

ONE instrument measures

Current A.C. and D.C. (0 to 10 amps)
A.C. and D.C. voltage (0-1,000 volts)
Resistance (up to 40 megohms)
Capacity (0 to 20 mfds.)
Audio-frequency Power Output (0 to 4 watts)
Decibels (−10 db to + 15 db.)

WHEREVER electrical apparatus is used the AvoMeter should be on the spot. A self-contained precision A.C./D.C. instrument, the Model 7 Universal AvoMeter has 46 ranges providing for all the measurements listed on the left. The ranges are quickly selected by means of two rotary switches. (No external shunts or series resistances required.) Conforming to B.S. 1st grade accuracy requirements, the meter is provided with automatic compensation for variations in ambient temperature, and is protected by an automatic cut-out against damage through overload.

Write for fully descriptive pamphlet.

16 Gns. Resistance range Extension Unit (for measurements down to 1/100th ohm) 12/6

Also the 36-range Universal AvoMeter .. .. 13 gns
22-range D.C. AvoMeter 9 gns.
Leather Carrying Case .. 25/-

DEFERRED TERMS IF DESIRED.

The 46-RANGE UNIVERSAL AVOMETER

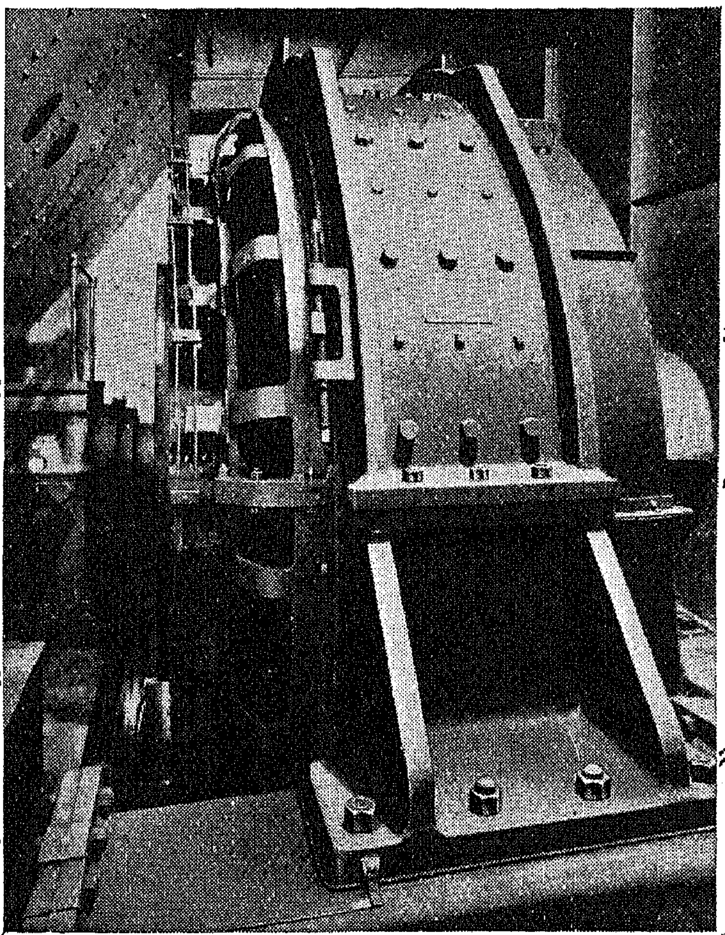
Regd. Trade Mark

Electrical Measuring Instrument *Model* 7

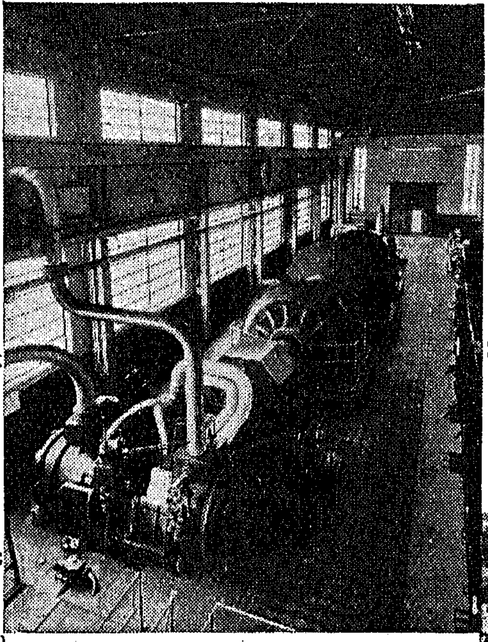
Sole Proprietors and Manufacturers :—
THE AUTOMATIC COIL WINDER & ELECTRICAL EQUIPMENT CO. LTD.
Winder House, Douglas Street, London, S.W.1. 'Phone: Victoria 3404/7

BRITON FERRY

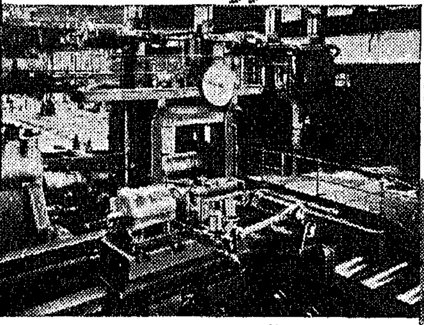
The Electrical Equipment of a Sheet Bar Mill



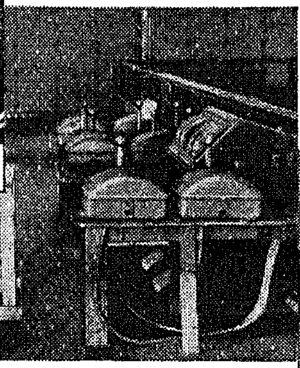
2,900 h.p. D.C. Roughing Mill Motor.



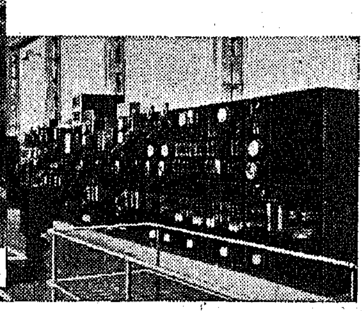
The Power House, with Turbo-flywheel Generator Set.



Main Reversing Mills.



Roughing Mill Control.



Main Control Switchboard.

Yet another important contribution towards the increased efficiency of well-known works throughout the country is the "Metrovick" Electrical Equipment of the new Sheet Bar Mill at the Albion Works of the Briton Ferry Steel Company.

This unique equipment, embodying the dual turbine-driven flywheel generator set, is representative of the adaptability of the technical and manufacturing resources of the Company to meet special local conditions. Whatever your steelworks drive problem, submit it to us for the most economical solution.

METROPOLITAN Vickers
ELECTRICAL CO., LTD.
TRAFFORD PARK ··· MANCHESTER 17.

COSMOS LAMPS will be used on the "Queen Elizabeth"

ELECTRICITY SUPPLY
(METERS) ACT, 1936.

★

THE instrument illustrated is the Laboratory Standard D.C. Voltmeter (Moving Coil) with 12-inch scale, recommended for use in conjunction with our D.C. Potentiometer for the periodical testing of Sub-standard Wattmeters. *Vide Supplementary Notes, paragraph 9.* **Accuracy : 0.1 per cent. of maximum scale reading. Diagonally divided scale.**

HAVE YOU ANY METER TESTING PROBLEMS?

We may be able to help you solve them and we can certainly help you to obtain the best instrument equipment for Meter testing, in accordance with the requirements of the Electricity Supply (Meters) Act, 1936.

ELLIOTT

Write for Catalogue
ELLIOTT BROTHERS
(LONDON) LIMITED
CENTURY WORKS,
LEWISHAM, S.E.13
ESTABLISHED——1800

LIST OF ADVERTISERS IN THIS ISSUE

	PAGE
Automatic Coil Winder & Electrical Equipment Co., Ltd.	xiv
Automatic Telephone & Electric Co., Ltd.	x
Babcock & Wilcox, Ltd.	xiii
British Aluminium Co., Ltd.	iii
British Insulated Cables, Ltd.	ii
British Thomson-Houston Co., Ltd.	xviii
Cable Makers' Association	xii
Chamberlain & Hookham, Ltd.	xvii
Davidson & Co., Ltd.	xi
Dubilier Condenser Co. (1925), Ltd.	i
Elliott Brothers (London), Ltd.	xvi
Ferranti, Ltd.	v
Metropolitan-Vickers Electrical Co., Ltd.	xv
Nalder Brothers & Thompson, Ltd.	xvii
Smith Meters, Ltd.	viii & ix
Standard Telephones & Cables, Ltd.	iv
Stewarts and Lloyds, Ltd.	vi
Westinghouse Brake & Signal Co., Ltd.	vii
Zenith Electric Co., Ltd.	xiv

I.E.E. PUBLICATIONS

The Journal.

Published monthly, and circulated free of charge to members of all classes. Single Numbers: members of all classes, 5s. 3d.; non-members, 10s. 6d.

Ten-Year Index to the Journal.

To Vols. 1–10 (1872–82), 2s. 6d.; 11–20 (1882–91), 2s. 6d.; 21–30 (1891–1901), 2s. 6d.; 31–47 (1901–1911), 2s. 6d.; 48–59 (1912–21), 2s. 6d.; 60–69 (1922–31), 10s. 6d.

Proceedings of the Wireless Section.

Published two or three times yearly, and circulated free of charge to members of the Wireless Section. Additional Numbers: members of all classes, 2s. 6d.; non-members, 5s.

Students' Quarterly Journal.

Published in March, June, September, and December, and circulated free of charge to Students, and Graduates under the age of 28. Single Numbers: members of all classes, 1s. 6d.; non-members, 2s. 6d. Annual Subscription: members of all classes other than Students, and Graduates under the age of 28, 6s.; non-members, 10s.

Science Abstracts (Section A, Physics; Section B, Electrical Engineering).

Published monthly. Consists of full abstracts from the leading Scientific and Technical Journals of the whole world, thus presenting in a form convenient for immediate reference a complete and concise record of the progress of Electrical Engineering and Physical Science. Single Numbers: members of all classes, 1s. 9d.; non-members, 3s. 6d. Annual Subscription: members of all classes other than Students, and Graduates under the age of 28, one Section 12s. 6d., both Sections 20s. Students, and Graduates under the age of 28, one Section 5s., both Sections 7s. 6d.; non-members, one Section 35s., both Sections 60s.

History and Objects of the Institution.

Supplied free of charge to both members and non-members.

Catalogue of the Lending Library.

Revised 1936. Supplied free of charge to members.

Regulations for the Electrical Equipment of Buildings (formerly I.E.E. Wiring Rules).

Tenth edition, September 1934. Bound in cloth covers, 1s. 6d. (postage 3d.). Bound in paper covers, 1s. (postage 2d.).

Regulations for the Electrical Equipment of Ships.

Second edition, June 1926. Bound in cloth covers, 3s. 6d. (postage 2d.). Bound in American cloth covers, 2s. 6d. (postage 2d.).

Model Forms of General Conditions.

Form A. For Home Contracts (with erection). Revised 1938. 2s. (postage 2d.).

Form B1. For Export (delivery f.o.b.). Revised December 1928. 1s.

Form B2. For Export (including complete erection or supervision of erection). Revised December 1928. 1s.

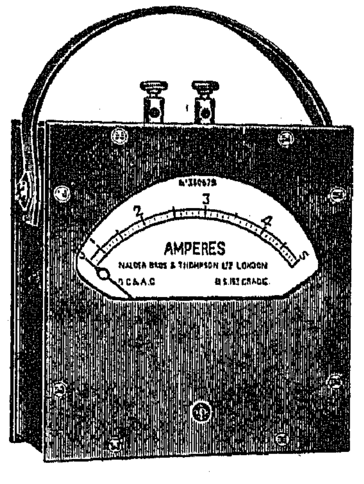
Form C. For the Sale of Goods other than Cables (Home, without erection). Issued April 1924. 6d.

Form D. For the Sale of Cables (Home, without erection). Issued April 1924. 6d.

Papers set at the Graduateship Examination.

Price 1s. per set.

The above publications are post free except where otherwise stated. They can be obtained from the Secretary of The Institution of Electrical Engineers, Savoy Place, Victoria Embankment, London, W.C.2, or from Messrs. E. and F. N. Spon, Ltd., 57 Haymarket, London, S.W.1.



NALDERS

PORTABLE INSTRUMENTS

AMMETERS
VOLT METERS
WATT METER

A.C. and D.C. Sub-standard and Industrial

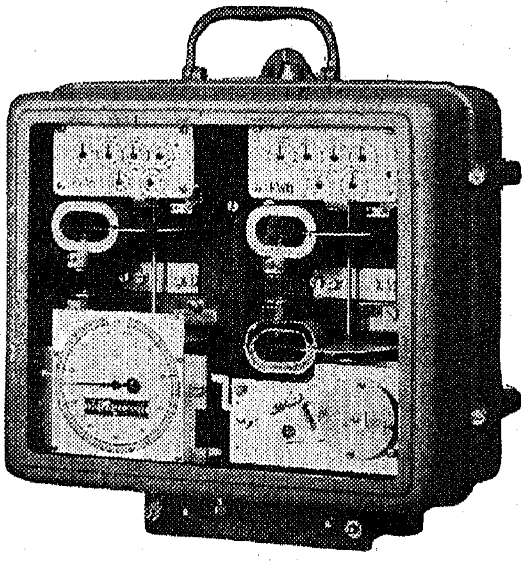
Ask for quotations

NALDER BROS & THOMPSON LTD

'Phone: CLISSOLD 2365 (3 lines).
'Grams: OCCLUDE, HACK, LONDON.

DALSTON LANE WORKS,
LONDON, E.8.

N C S



C&H

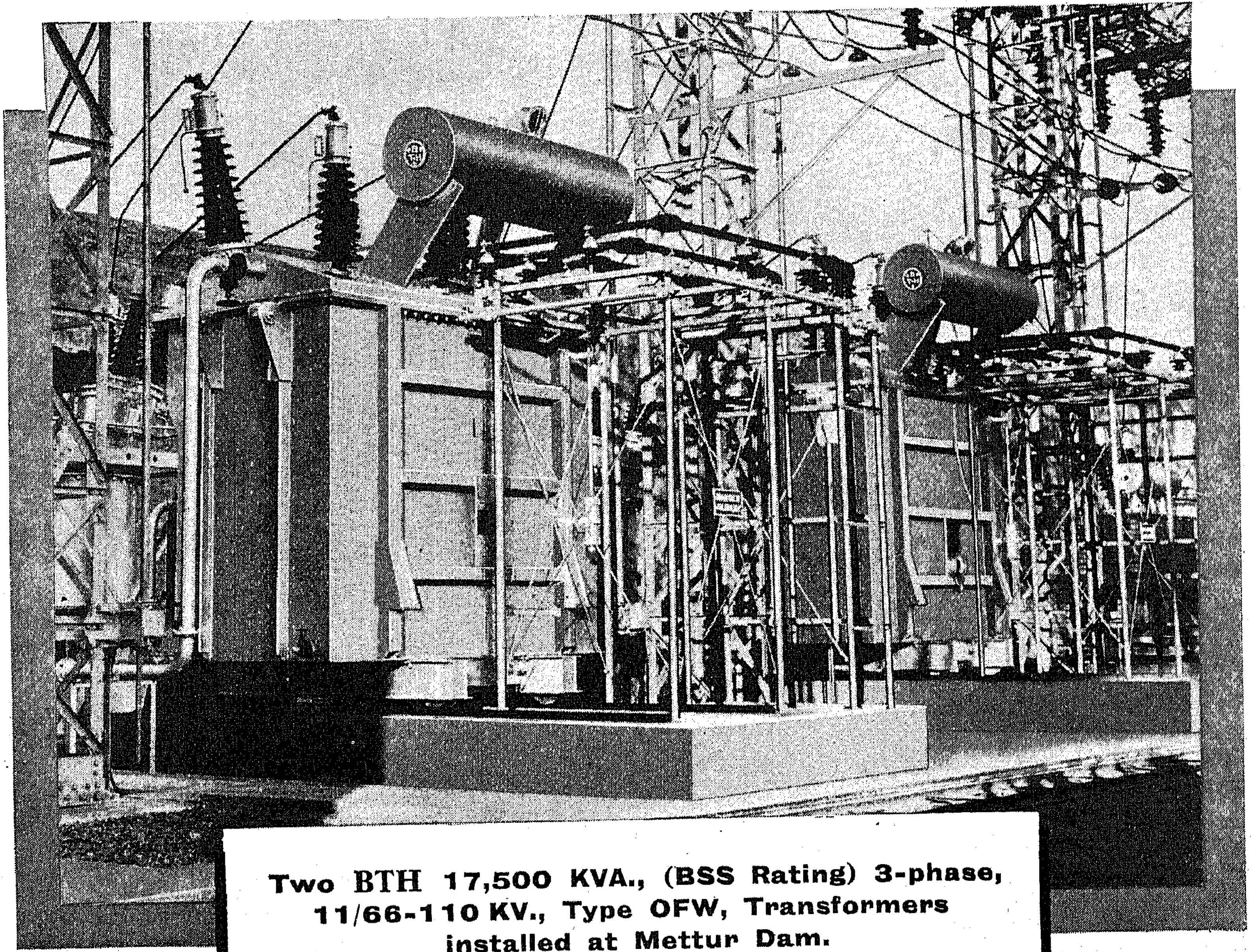
POLYPHASE K.W.H. METER
WITH
K.V.A. DEMAND INDICATOR

SIMPLICITY—always a feature of C. & H. design—is strongly evident in this combination Meter. One set of terminals and connections ensures correct installation. The testing and adjustment of the meter is simplicity itself.

Manufacturers:

CHAMBERLAIN & HOOKHAM, Ltd.
SOLAR WORKS, NEW BARTHOLOMEW STREET
BIRMINGHAM
London Office: Magnet House, Kingsway, W.C.2

TRANSFORMERS



Two BTH 17,500 KVA., (BSS Rating) 3-phase, 11/66-110 KV., Type OFW, Transformers installed at Mettur Dam.
Mettur Hydro-electric Development, Government of Madras, India.

These Transformers were subjected to impulse tests with full and chopped waves, on a gap of 26$\frac{3}{8}$", corresponding to a full wave impulse voltage of 400 KV.

We make all types of TRANSFORMERS

BTH RUGBY

THE BRITISH THOMSON-HOUSTON COMPANY LIMITED, RUGBY, ENGLAND.

A2565

LOCAL CENTRES AND SUB-CENTRES—*Continued.*

NORTH-WESTERN CENTRE.

Chairman.—W. Fennell.

Hon. Secretary.—L. H. A. Carr, M.Sc.Tech., "Oakleigh," Cambridge Road, Hale, Altrincham, Cheshire.

SCOTTISH CENTRE.

Chairman.—W. J. Cooper.

Hon. Secretary.—R. B. Mitchell, 154, West George Street, Glasgow, C.2.

Hon. Assist. Secretary.—H. V. Henniker, 172, Craigleith Road, Edinburgh.

Dundee Sub-Centre.

Chairman.—G. F. Moore, B.Sc.

Hon. Secretary.—P. Philip, c/o Electricity Supply Dept., Dudhope Crescent Road, Dundee.

SOUTH MIDLAND CENTRE.

Chairman.—H. Faulkner, B.Sc.

Hon. Secretary.—R. H. Rawll, 65, New Street, Birmingham.

East Midland Sub-Centre.

Chairman.—T. Rowland.

Hon. Secretary.—J. F. Driver, Brighton House, Herrick Road, Loughborough.

WESTERN CENTRE.

Chairman.—H. S. Ellis.

Hon. Secretary.—G. L. Coventon, 126, London Road, Gloucester.

Devon and Cornwall Sub-Centre.

Chairman.—H. Midgley, M.Sc.

Hon. Secretary.—F. C. Isaac, Council Offices, Plympton, South Devon.

West Wales (Swansea) Sub-Centre.

Chairman.—J. E. Dawtry.

Hon. Secretary.—R. Richards, 78, Glanbrydan Avenue, Swansea.

Hampshire Sub-Centre (directly under the Council).

Chairman.—W. S. Lonsdale.

Hon. Secretary.—A. G. Hiscock, c/o City of Portsmouth Electricity Undertaking, 111, High Street, Portsmouth, Hants.

Northern Ireland Sub-Centre (directly under the Council).

Chairman.—F. Johnston.

Hon. Secretary.—J. McCandless, M.Sc., Burn Brae, Strangford Avenue, Belfast.

INFORMAL MEETINGS.

Chairman of Committee.—

METER AND INSTRUMENT SECTION.

Chairman.—Captain B. S. Cohen, O.B.E.

TRANSMISSION SECTION.

Chairman.—S. R. Siviour.

WIRELESS SECTION.

Chairman.—A. J. Gill, B.Sc.(Eng.).

OVERSEAS COMMITTEES.

AUSTRALIA.

New South Wales.

Chairman.—V. L. Molloy.

Hon. Secretary.—W. J. McCallion, M.C., c/o Electrical Engineers Branch, Dept. of Public Works, Sydney.

Queensland.

Chairman and Hon. Secretary.—J. S. Just, c/o P.O. Box 1067n, G.P.O., Brisbane.

South Australia.

Chairman and Hon. Secretary.—F. W. H. Wheadon, Kelvin Building, North Terrace, Adelaide.

Victoria and Tasmania.

Chairman and Hon. Secretary.—H. R. Harper, 22–32, William Street, Melbourne.

Western Australia.

Chairman.—J. R. W. Gardam.

Hon. Secretary.—A. E. Lambert, B.E., 35, The Esplanade, South Perth.

CEYLON.

Chairman.—Major C. H. Brazel, M.C.

Hon. Secretary.—D. P. Bennett, c/o Messrs. Walker Sons & Co., Ltd., Colombo.

INDIA.

Bombay.

Chairman.—R. G. Higham.

Hon. Secretary.—A. L. Guilford, B.Sc.Tech., Electric House, Post Fort, Bombay.

Calcutta.

Chairman.—F. T. Homan.

Hon. Secretary.—D. H. P. Henderson, c/o Calcutta Electric Supply Corporation, Post Box 304, Calcutta.

Lahore.

Chairman.—Prof. T. H. Matthewman.

Hon. Secretary.—J. C. Brown, c/o Associated Electrical Industries (India) Ltd., P.O. Box 146, Lahore.

Madras.

Chairman and Hon. Secretary.—E. J. B. Greenwood, Electricity Dept., P.W.D. Offices, Chepauk, Madras.

NEW ZEALAND.

Chairman.—F. T. M. Kissel, B.Sc.

Hon. Secretary.—J. McDermott, P.O. Box 749, Wellington, C.1.

SOUTH AFRICA.

Transvaal.

Chairman and Hon. Secretary.—W. Elsdon Dew, Box 4563, Johannesburg.

LOCAL HONORARY SECRETARIES ABROAD.

ARGENTINE: R. G. Parrott, Tucuman 117, Buenos Aires.

CANADA: F. A. Gaby, D.Sc., Vice-President, The British American Oil Co., Ltd., 14th Floor, Royal Bank Building, Toronto, Ontario.

CAPE, NATAL, AND RHODESIA: G. H. Swingler, City Electrical Engineer, Corporation Electricity Dept., Cape Town.

FRANCE: P. M. J. Ailleret, 20, Rue Hamelin, Paris (16e).

HOLLAND: A. E. R. Collette, Heemskerckstraat, 30, The Hague.

INDIA: K. G. Sillar, c/o Calcutta Electric Supply Corporation, Post Box 304, Calcutta.

ITALY: L. Emanueli, Via Fabio Filzi, 21, Milan.

JAPAN: I. Nakahara, No. 40, Ichigaya Tanimachi, Ushigomeku, Tokio.

NEW SOUTH WALES: V. J. F. Brain, B.E., Chief Electrical Engineer, Department of Public Works, Bridge Street, Sydney.

NEW ZEALAND: J. McDermott, P.O. Box 749, Wellington, C.1.

QUEENSLAND: J. S. Just, c/o P.O. Box 1067n, G.P.O., Brisbane.

SOUTH AUSTRALIA: F. W. H. Wheadon, Kelvin Building, North Terrace, Adelaide.

TRANSVAAL: W. Elsdon Dew, Box 4563, Johannesburg.

UNITED STATES OF AMERICA: Gano Dunn, c/o The J. G. White Engineering Corporation, 80, Broad Street, New York, N.Y.

VICTORIA AND TASMANIA: H. R. Harper, 22–23, William Street, Melbourne.

WESTERN AUSTRALIA: Prof. P. H. Fraenkel, B.E., The University of Western Australia, Crawley, Perth.

STUDENTS' SECTIONS.

LONDON.

Chairman.—P. H. Pettifor.
Hon. Secretary.—A. H. Young, "Park View," Alton Road, Roehampton, S.W.15.

NORTH-WESTERN.

Chairman.—R. Noonan.
Hon. Secretary.—R. M. A. Smith, Meter Engineering Dept., Metropolitan-Vickers Electrical Co., Ltd., Trafford Park, Manchester, 17.

SCOTTISH.

Chairman.—J. Brown.
Hon. Secretary.—G. H. Wire, c/o Mrs. Cormie, 8, Townhead Terrace, Paisley.

NORTH-EASTERN.

Chairman.—F. M. Bruce.
Hon. Secretary.—J. A. Stanfield, 44, Shipley Avenue, Milvain, Newcastle-on-Tyne.

MERSEY AND NORTH WALES (LIVERPOOL).

Chairman.—T. E. A. Verity, B.Sc.Tech.
Hon. Secretary.—W. H. Penley, B.Eng., Laboratories of Applied Electricity, The University, Liverpool, 3.

SOUTH MIDLAND.

Chairman.—J. E. Woollaston.
Hon. Secretary.—B. S. Copson, 88, Reservoir Road, Olton, Birmingham.

NORTH MIDLAND.

Chairman.—A. H. Marsh.
Hon. Secretary.—G. H. Warne, 6, Parkfield Road, Shipley, Yorkshire.

SHEFFIELD.

Chairman.—H. A. Wainwright, B.Eng.
Hon. Secretary.—C. C. Hall, 4, Meadow Head Avenue, Woodseats, Sheffield, 8.

BRISTOL.

Chairman.—W. H. Small.
Hon. Secretary.—J. W. Dorrington, 20, Trelawney Road, Cotham, Bristol, 6.

THE I.E.E. BENEVOLENT FUND.

THE COUNCIL HAVE KINDLY GRANTED THE USE OF THIS SPACE IN ORDER THAT THE BENEVOLENT FUND MAY BE BROUGHT MORE EFFECTIVELY TO THE NOTICE OF THE MEMBERS OF THE INSTITUTION.

The object of the Fund is: "To afford assistance to necessitous members and former members (of any class) of The Institution of Electrical Engineers who have paid their subscriptions for at least five years consecutively or compounded therefor, and to the dependants of such members or former members."

Subscriptions and Donations should be addressed to

THE HONORARY SECRETARY, THE BENEVOLENT FUND,
THE INSTITUTION OF ELECTRICAL ENGINEERS,
SAVOY PLACE, W.C.2.

⁂

LOCAL HON. TREASURERS OF THE FUND.

Irish Centre: T. J. Monaghan. *North-Eastern Centre:* N. Cresswell. *North Midland Centre:* R. M. Longman. *Sheffield Sub-Centre:* W. E. Burnand. *North-Western Centre:* T. E. Herbert. *Mersey and North Wales (Liverpool) Centre:* A. C. Livesey. *Scottish Centre: (Glasgow)* A. Lindsay; *(Edinburgh)* D. S. Munro. *Dundee Sub-Centre:* P. Philip. *South Midland Centre:* W. Y. Anderson. *Western Centre: (Bristol)* E. P. Knill; *(Cardiff)* J. W. Elliott. *Hampshire Sub-Centre:* W. P. Conly, M.Sc.

PRINTED BY UNWIN BROTHERS LIMITED, LONDON AND WOKING